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BACTERIAL MOVEMENT THROUGH FRACTURED BEDROCK

by

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COLORADO WATER RESOURCES RESEARCH INSTITUTE

Colorado State University
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BACTERIAL MOVEMENT THROUGH FRACTURED BEDROCK

A SUBPROJECT OF
SYSTEM FOR GEOLOGIC EVALUATION
OF POLLUTION POTENTIAL AT MOUNTAIN DWELLING SITES

Partial Completion Report

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by

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ABSTRACT

BACTERIAL MOVEMENT THROUGH FRACTURED BEDROCK

The movement of bacteria-laden waters percolating through fractured bedrock was examined to determine whether effluent originating from conventional waste disposal systems could contaminate shallow ground water supplies. Inoculated waters were injected into holes and/or wells at two geologically different test sites to evaluate the extent of microbial filtration of leachfield effluent in or along bedrock fractures. Microbiological examination of tracer waters, sampled both above and below the zone of saturation, were made.

Field studies showed that the direction and rate of movement of contaminated ground waters were controlled largely by the anisotropic nature of the geologic stratum, particularly by the orientation of major bedrock fracture sets. Injection waters, inoculated with Bacillus stearothermophilis, were found to be readily transported by the ground water gradient into a downslope well. At the Parvin Lake site the tracer bacterium traversed a horizontal distance of 94 ft. in 24-30 hr. Continued bacteriological analysis of the contaminated well found the tracer bacterium to be present for at least 6 days after inoculation of the upslope well.

In the zone of aeration, bacteria-laden effluent was found to percolate rapidly in or along bedrock fractures with inadequate filtration of the effluent occuring prior to entering potable ground water supplies. Studies conducted in a metamorphic rock formation demonstrated that while fecal-type bacteria decreased slightly during percolation through bedrock fractures, total bacterial densities were generally higher or unchanged following percolation.

Additional laboratory studies on 28 rock samples found microbial die-off rates as a result of toxicity due to the mineralogy of some common rock types to be negligible.

From the hydrolgeological and microbiological data obtained at both test sites, it can be concluded that moderate percolation rates and minimum distances between water-wells and conventional waste disposal units are inadequate to protect potable ground water supplies from contamination in mountainous terrains. Thus, on most mountain building sites, it is essential that either hydrogeologic data, such as bedrock fracture patterns, depth and movement of ground waters, seasonal fluctuations in ground water levels, be fully ascertained prior to installation of soil-absorption systems or alternate waste disposal methods should be selected.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

In sparsely settled rural non-mountain areas, the requirement for potable water is usually satisfied by shallow dug or drilled wells and domestic wastes are processed through septic tanks, cesspools, and soil-absorption systems. Ground waters from properly constructed and maintained wells are produced in moderate quantities and are generally adequate biologically. While domestic waste disposal systems provide minimal waste treatment, the possibility of contaminating the ground water supply by effluent is minimized since: 1) wells and waste disposal facilities can be located far enough apart, 2) the quantities of waste are consistent and small enough for adequate purification, 3) the depth to the aquifer and/or bedrock is considerable, and most important, 4) the subsoil profile and texture is generally more than sufficient for effluent purification.

In mountainous regions, where soils are sparse or non-existent, the possibility of contaminating local ground water supplies by domestic wastes is greatly increased. Further, with the accelerated growth of mountain communities, the uneven waste loading of disposal systems due to seasonal and recreational activities, and the lack of municipal water and waste treatment facilities, pollution of mountain water supplies is prevalent in many areas. Microbiological

examination of ground water in selected areas has revealed that a large percentage of wells contained elevated coliform counts; indicating contamination from fecal sources such as domestic waste disposal systems. Areas examined included the foothills of the Colorado Front Range between Golden and Fort Collins, the Red Feather Lakes region of northern Colorado, and Cache La Poudre Canyon northwest of Fort Collins. State and federal health agencies have characteristically relied upon horizontal and vertical displacement between waste disposal systems and water wells to prevent contamination of potable ground waters.

Thus, the present methodology for developing domestic waste disposal systems in mountainous areas must be re-evaluated to protect shallow ground water from contamination. This investigation has endeavored to determine, in part, which geologic parameters affect both the movement of bacteria-laden waste waters into mountain ground water supplies and the survival of the microbial contaminants introduced into ground water.

The objectives of this study were to:

1) determine whether microorganisms present in percolating water could be transported through fractured bedrock,

2) determine the extent of bacterial movement through fractured and/or jointed bedrock at or below the water table,

3) evaluate, in controlled laboratory procedures, the geochemical and mineralogical affects on the survival of fecal-type bacteria.

Bacterial movement through rock fractures was monitored at two mountain sites. Inoculated waters were introduced through hand-dug or drilled holes into various geologic settings. After flowing through fractured bedrock, recovered inoculated waters were analyzed for bacterial numbers. A tracer organism was used to quantify bacterial movement through the saturated zone. Mineralogical and/or geochemical affects on bacterial survival were studied by inoculating fecal-type bacteria into crushed rock-water aggregates of varying geologic origins. Relative die-off rates were determined from daily cell counts on each aggregate sample. Statistical correlations of the varying mineralogical constituents were made to determine whether an element or group of elements could account for some of the differing die-off rates.

REVIEW OF LITERATURE

The utilization of ground waters generally occurs when surface water supplies are insufficient, unavailable, or require extensive purification to render the water potable. Undisturbed aquifers produce moderate quantities of water which are low in dissolved solids and characteristically free of enteric pathogens. During the past twenty years, however, researchers have noted increased levels of pollutants in shallow ground water supplies. Many investigators (12, 13, 14, 20, 21, 22, 26, 27, 29, 32, 34, 40, 41) attribute this decline in ground water quality to the indiscriminate use of septic-tank soil-absorption systems in terrains unsuited for adequate domestic waste purification. With the accelerated growth of mountain communities and the lack of municipal water and waste treatment facilities, individual waste treatment units such as septic tanks have been widely used for processing domestic wastes. These methods of waste treatment have, unfortunately, resulted in local chemical and biological contamination of ground waters.

The majority of studies dealing with ground water contamination have been in regions underlain by sedimentary formations, unconsolidated glacial drift, and nonindurated sediments. Virtually none of the investigations to date has dealt with ground water contamination problems associated with metamorphic or igneous rock. While the

number of publications concerned with the movement of microorganisms through fractured rock is very limited, ground water problems in non-crystalline rock formations relate, in part, to this study. Considered in this review will be (i) the nature of ground water contaminants, (ii) domestic waste disposal systems and well-water supplies, and (iii) geologic controls upon ground water occurence and movement.

The Nature of Ground Water Contaminants

Shallow aquifers, which are the most important sources of potable water in mountainous areas, are also the most susceptible to contamination by substances inadvertently introduced from the surface by man. In addition, once an aquifer has been polluted, it is exceedingly difficult and sometimes economically unfeasible to reclaim it even after the source of contamination is removed. Ground water contaminants are commonly classified as biological or chemical (inorganic or organic).

Disease outbreaks associated with contaminated ground water supplies are well documented (25, 29, 34, 36). Robeck (29) attributed outbreaks of Asiatic cholera, infectious hepatitis, and salmonellosis to improper disposal of domestic sewage. In an extensive review of water-borne hepatitis, Taylor and co-workers (34) noted viral outbreaks to be caused by seepage of sewage from septic tanks and privies through creviced limestone into adjacent

wells. Taylor also reported higher hepatitis rates in comparison with national rates in the Rocky Mountains, Appalachian Mountains, New England States, and Alaska. Although surface waters in these hard-rock terrains receive little treatment prior to use, induced infiltration of contaminated surface waters into nearby shallow wells cannot be discounted.

In additional studies (11, 30) on viral travel through soils it was concluded that a distance of 50-100 ft. between waste disposal systems and wells is advisable. In the majority of cases in which viruses appeared to have traveled through the soil, evidence indicated that channeling through fissued or fractured substrata had occured. Romero (31), however, cautions that areas having discontinuous soils and underlain by igneous, metamorphic, or consolidated sedimentary rocks should be given a more critical examination because of the possibility of extensive viral and bacterial travel via fractures, joints, and solution channels.

While it is virtually impossible to develop any water supply without having some bacteria present, the presence of enteric microorganisms in well-water, particularly in suburban areas dependent on ground water sources, indicates gross contamination of shallow aquifers by domestic waste effluent. The isolation of enteric pathogens, both viral and bacterial, from waste-associated waters is generally impractical in that microbiological techniques available

for identification of such organisms are time-consuming and complicated. For this reason, coliform bacteria are routinely used as indicators of water contamination. Although this group of organisms is not characteristically pathogenic, its presence in water supplies is closely associated with fecal contamination.

In a study of more than 63, 000 wells in unsewered areas of Minnesota, 50% of the well-water supplies in older suburban communities were found to contain coliforms (41). Investigators attributed the contamination of the wells to improper waste disposal. Hackett(14) reported that bacterial contamination of shallow dolomite aquifers to be a regional problem in Illinois. Additional work by Walker (39) and Wall and Webber (40) confirm that limestone and dolomite aquifers tend to be extensively fractured and jointed, thus providing open linear channels for the movement of bacteria-laden water. While a direct hydrogeologic connection between ground water and leachfield is difficult to demonstrate, there are numerous reports (21, 32, 33, 38, 41) incriminating septic-tank effluent with elevated enteric counts. Listed as parameters governing the extent of shallow ground water contamination are: 1) well depth and type construction, 2) population density, 3) lot size, 4) depth and texture of soil, 5) structure of subsoils, 6) time of year, 7) incident precipitation, and 8) direction and rate of ground water movement.

The distances traveled by bacteria through the substrata vary considerably. McGauhey and Krone (25) in reviewing studies on bacterial movement into ground water concluded that most microorganisms, including coliforms and fecal streptococci, are removed from percolating ground waters within the first 200 ft. of travel, although bacteria have been reported to have traveled over 800 ft. Furthermore, Krone (17) and others (5, 18, 24) have demonstrated that self-purification of bacteria-laden waters through natural die-off must be discounted. Studies have shown bacterial survival to be encouraged by reduced temperature, near neutral pH, adequate moisture, and the absence of antagonistic organisms. Such conditions are typically found in shallow aquifers.

Chemical contamination of ground waters include both organic and inorganic substances. Organic compounds commonly reported in polluted aquifers include detergents (alkyl benzene sulfonates, linear alkylated sulfonates), phenolic derivatives, cresols, and petroleum products (25, 36, 41). While organics at low concentrations are seldom harmful to the consumer, they do impart taste, color, odor, and foaming which are offensive. Furthermore, organic contaminants which are ordinarily degraded readily in surface waters, are extremely persistent in ground waters. The presence of petroleum products such as gasoline and kerosene results most often from leaky subterranean storage tanks and accidental spills (13). High and

persistent levels of detergents in shallow aquifers is most often associated with malfunctioning septic-tank systems and sewage lagoons (16, 22, 23, 40, 41).

Inorganic constituents of polluted aquifers include such ions as manganese, iron, chloride, cadmium, sulfate, nitrate, nitrite, phosphate, sodium, calcium, magnesium, boron, chromium, and occasionally radionuclides (25, 36). Abnormally high levels of cations such as manganese, iron, cadmium, and chromium are most often associated with industrial sources, i.e., waste-holding ponds, injection wells, whereas the presence of nitrates, nitrites, and organophosphates result from incomplete degradation and/or filtration of domestic wastes prior to entering ground water supplies (23, 25, 40, 41). Increasing salt concentrations in shallow ground waters are also due, in part, to leachfield effluent (25, 27).

Domestic Disposal Systems and Water Supplies

In rural or suburban areas, where municipal waste treatment facilities are often unavailable, domestic wastes are treated by septic tanks, cesspools, and soil-absorption fields. The requirement for potable water is usually satisfied by shallow dug or drilled wells. Contamination of adjacent wells by properly designed and maintained waste disposal facilities is considered remote since: 1) well and disposal systems can be located far enough apart, 2) the quantities of waste are small enough for efficient purification, 3) depth to the

aquifer is considerable, and most important, 4) the soil depth and texture is generally more than sufficient for effluent filtration.

A majority of homeowners select a septic-tank soil-absorption system for domestic waste treatment when service from an acceptable municipal waste treatment system is not available or feasible (4). While septic tanks are extremely inefficient in comparison to municipal treatment systems, they do provide adequate treatment of domestic wastes when properly designed, installed, and maintained. Because untreated household wastes will quickly clog all but the most porous formations, septic tanks are required to condition waste water prior to disposal through the subsoil (37). Thus, the function of septic tanks is threefold: 1) removal of solids by settling through reduced flow rates, 2) partial anaerobic decomposition of organic materials, and 3) storage of inert solid material (grit) and organic residues. Discharge effluent from properly operating tanks, while high in microbial numbers, is, nonetheless, substantially lower in suspended solids and soluble organic constituents. It is, therefore, the function of the soil-absorption system to effectively remove potential bacterial and viral pathogens as well as organic components from waste effluent prior to entering shallow ground waters.

To cope with insufficient information concerning local ground water contamination due, in part, to leachfield effluent, public health agencies have relied upon horizontal and vertical distances

between wells and waste disposal systems to protect potable water supplies. Federal health agencies suggest that septic tanks and leachfields should never be closer than 50 ft. from any source of water supply (37), and a greater distance if possible. Presently, Colorado requires a minimum of 100 ft. between waste disposal systems and any well-water supply; 50 ft. from any stream or water course (6). Recent studies (1, 21) have shown, however, that while mandatory distances between waste disposal sites and well-water supplies are generally adequate in protecting potable ground water supplies, many urban size lots are incapable of absorbing all the sewage effluent produced by an average household. Furthermore, years of experience have proven that soil-absorption systems are incapable of working well except in rural areas or in soils where the discharge from waste systems is readily absorbed and conditioned prior to entering the ground water supply.

The chemical and microbiological quality of percolating ground waters derived from waste effluent is directly related to soil depth, texture, and type. While it is erroneous to base soil suitability solely on soil depth beneath an absorption field, the majority of published guidelines (7, 22, 37) recommend a minimum of 4-5 ft. of "suitable" subsoil to adequately filter septic-tank effluent. There are, however, some reports (9, 30) which contend that soil depth is not a sufficient criterion to protect shallow ground water supplies; the type

and texture of the subsoil must also be weighed heavily. Subsoils containing relatively large percentages of gravels and sands, with little clay minerals present, characteristically give high percolation rates, but are completely unsuited for waste water filtration. In contrast, subsoils composed predominately of clay, while possessing high filtration capabilities and low percolation rates, are economically unsuited for septic-tank systems due to the high cost of developing absorption fields large enough to process the volume of effluent produced by a household.

The removal of microorganisms from percolating waters by subsoils is basically an absorption phenomenon (5, 11, 40) although other environmental factors such as pH, chemical toxicity, natural die-off, mechanical sieving, presence of a zoogleal film, etc. are also significant. In mountainous terrains, where deep soil profiles are seldom developed, adequate microbial removal from percolating waste waters may, nonetheless, occur due to the absorption and toxic properties of certain minerals and/or the presence of weathered-in-place clay-producing minerals. Geochemical or pH alterations imparted to percolating waters by solubilization of bedrock minerals may, in some cases, effectively eliminate microbial contaminants.

Hydrogeologic Aspects of Shallow Ground Water Contamination

The utilization of shallow ground waters is largely dependent upon the availability and quality of surface waters. Although

phraeatic water is present to some extent under all land surfaces, geologic structures are only considered aquifers when they are able to consistently produce water in economic volumes. The occurence and movement of ground water is governed entirely by the hydrogeologic nature of the aquifer. Thus, bacteria-laden waters are subject to the same physical controls as potable supplies. The water-bearing properties of rocks are a function of both permeability and porosity (12).

Permeability or hydraulic conductivity relates to the ease in which fluids can flow through geologic formations. Characteristically, well-sorted gravel, porous basalt, cavernous limestones, and coarse nonindurated sediments have the highest permeability; dense crystalline rocks, clays, and silt have the lowest conductivity, with fractured crystalline rock considered average in permeability. In contrast, basalt, cavernous limestone, and crystalline rock, both fractured and dense, possess the lowest porosity. Well yields in metamorphic and plutonic igneous rocks are generally low, since the only water available to wells in such rock types occur in the joints, faults, and fractures. In mountainous terrains, where soils are often poorly developed, the possibility of leachfield effluent entering underlying fractured bedrock and eventually reaching adjacent wells is higher than in non-mountainous areas.

Ground water movement, both direction and rate, in crystalline rock is controlled exclusively by fractures, foliation, and hydraulic gradient. In dense consolidated sedimentary formations such as limestone and dolomite, permeability is determined principally by secondary openings such as joints and solution cavities (36). Widespread contamination of shallow limestone and dolomite aquifers is a critical problem in many areas (10, 14, 23, 31, 34). Sources of ground water contamination in such areas have been attributed to domestic waste disposal systems, sanitary landfills, interaquifer leakage as a result of industrial disposal wells, and certain agricultural practices (39). In several instances, contamination of shallow aquifers has resulted in abandonment or relocation of private and municipal wells. Although studies dealing with ground water pollution in sediments is limited, little is known about the travel of pollutants in areas underlain by crystalline rock formations (31).

Aside from fluvial deposits found in river and stream valleys, potable water supplies for a large percentage of the population living in mountain regions are derived from crystalline rock formations. Igneous and metamorphic rocks are essentially non-porous, but yield meager amounts of water from their secondary openings (8, 9). Fractures in crystalline rock are most numerous and widest at the soil-bedrock interface, and decrease in width and frequency with depth. This decrease of permeability is a result of the weight of

overlying rock and the inability of surface disturbances, such as weathering, to penetrate only a short distance into bedrock. Unlike alluvium and nonindurated sediments, increased water yields are not synonomous with increased well depth. Thus, in mountainous terrains, the majority of homes rely on shallow fractured bedrock as their source of potable water. Unfortunately, a large percentage of these same homes also dispose of domestic wastes through septic-tank soil-absorption systems and in some instances unvaulted privies. As a result of such waste disposal practices, a high percentage of shallow wells in some mountain areas have been found to contain abnormally high coliform counts (26).

The channeling of leachfield effluent, particularly viable bacteria, by fractured bedrock into adjacent wells is widely assumed (8, 9, 10, 11, 13, 14, 23, 31, 39, 40) although poorly documented for crystalline rock masses. Recently Freethy (12) and Millon (26) noted that geological and topographic variables were significant in the movement of contaminated ground water. Both investigators concluded that leachfield effluent readily percolates through fractured bedrock into adjacent well-water supplies.

MATERIALS AND METHODS

The materials and methods section is divided into: I. Field Procedures and, II. Laboratory Procedures. Field Procedures is further subdivided into: A. Bacterial Movement in the Zone of Saturation and, B. Bacterial Movement in the Zone of Aeration.

I. Field Procedures

A. Bacterial Movement in the Zone of Saturation

1. Site Location and Geologic Description: The Parvin Lake site is situated in the Red Feather Lakes area which is 41 miles northwest of Fort Collins, Colorado or 21 miles west of Livermore, Colorado (Figure 1). This site was chosen because: 1) previous geophysical, hydrological, and microbiological studies were completed in the near vicinity, 2) of the close proximity of the water table to the surface and 3) of its accessibility by the drill rig. Also Parvin Lake is state-owned with supervisory personnel on duty throughout the year.

Geologically this site is underlain by a Silver Plume Granite (26). Silver Plume is a porphyritic granite containing pink and gray feldspars, smoky quartz, biotite, and some muscovite. Of hydrogeologic interest is the unusual deep in-place weathering of this particular granite as well as the presence of at least three sets of

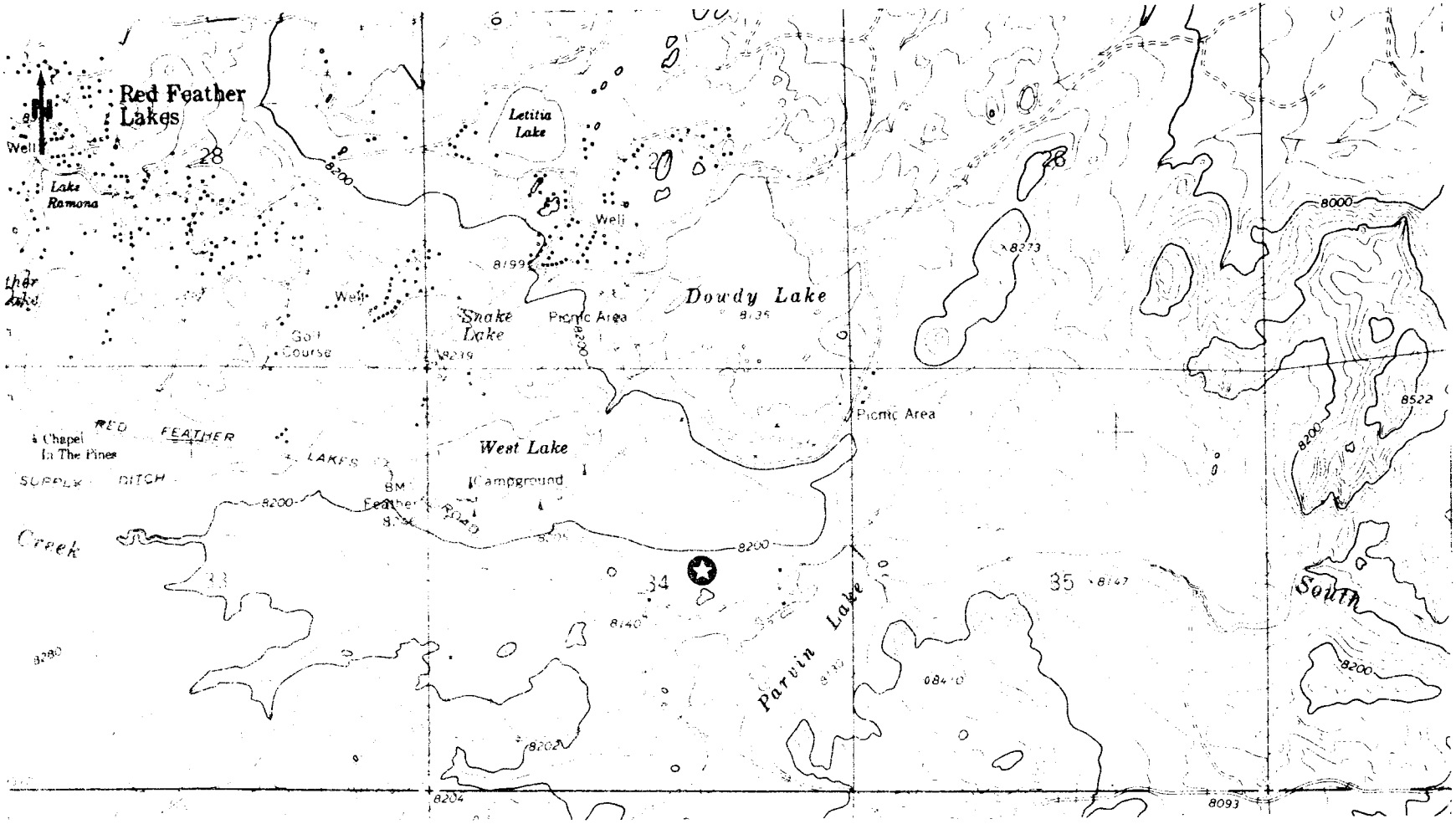


FIGURE 1. Parvin Lake Site - Red Feather Lakes Area, Colorado

Location: T10N, R73W, Section 34; Elevation: 8164'

Map taken from U. S. G. S. 7.5' Red Feather Lakes Quadrangle (1967) Scale = 1:24000; Contour Interval = 40'

joints (Figure 2). Depth of the weathered granite, as evidenced by an abrupt decrease in drilling rates, was approximately 15-17 ft. Joint patterns include: 1) a nearly vertical major joint set with a strike of N10°E, 2) a second prominent vertical joint set with a strike of N70°E, 3) an additional set of joints with an approximate strike of N35°E, and 4) horizontal exfoliation fractures (sheeting).

2. Site Development: On a nearly level area, a series of four wells, approximately 6 inches in diameter, were developed using a Model #55 rotary drill rig (Central Mining Co., St. Louis, Mo.) to depths ranging between 28 to 39 ft. (Figure 3). Initial drilling rates were 10-15 ft./hr. with a substantial rate reduction (less than 5 ft./hr.) occurring at a depth of 15-17 ft. Bentonite was added to circulatory water to facilitate removal of rock cuttings and to prevent the loss of drilling fluid in bedrock fractures. After attaining the desired depth, each well was flushed with 150-200 gallons of clean lake water to remove drilling mud/cuttings and then cased to a depth of 4 ft. with polyvinylchloride (PVC) plastic pipe. Water required for both the drilling operation and injection tests was obtained from Parvin Lake.

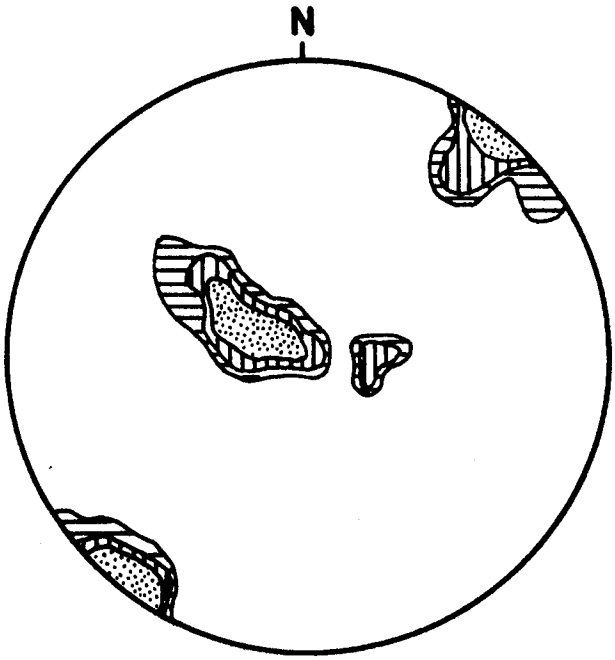
Elevations of the four wells and the horizontal distances between the wells were determined by plane-tabling (Figure 4). Approximate elevations of the contour intervals are based upon the static level of

FIGURE 2. Joint Diagrams (35) for the two test sites. The strike and dip of the bedrock fractures were obtained with a Brunton compass. This data was then plotted using the pole direction of the joints projected to the lower hemisphere on a Schmidt equal-area net. From the plotted points, a point diagram was prepared of points lying in an area equal to 1% of the total area. A contour map was then prepared using intervals of <5%, 5-10%, and >10%.

A) Cache La Poudre River Canyon site; 101 readings.

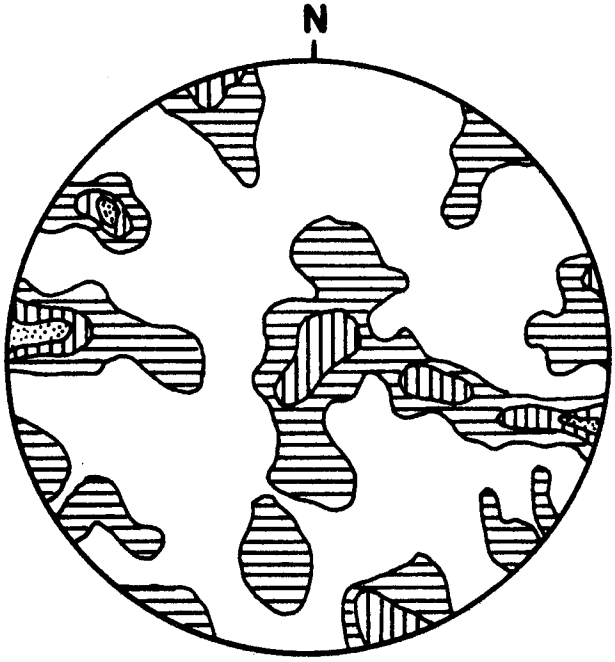
B) Parvin Lake Site (D. R. Beissel, M. S. Thesis, Colorado State University)

A



Contour Intervals: <5% 5-10% >10%

B



Contour Intervals: <5% 5-10% >10%

FIGURE 3. Photographs of Parvin Lake Site

A. Top view of site looking south-picture taken from atop adjacent rock outcrop; barrel in photo is next to monitoring hole #1.

B. Overall view of test site looking toward the northeast; note the two prominent fractures present in the rock outcrop in the bottom center of the photograph.

A

B

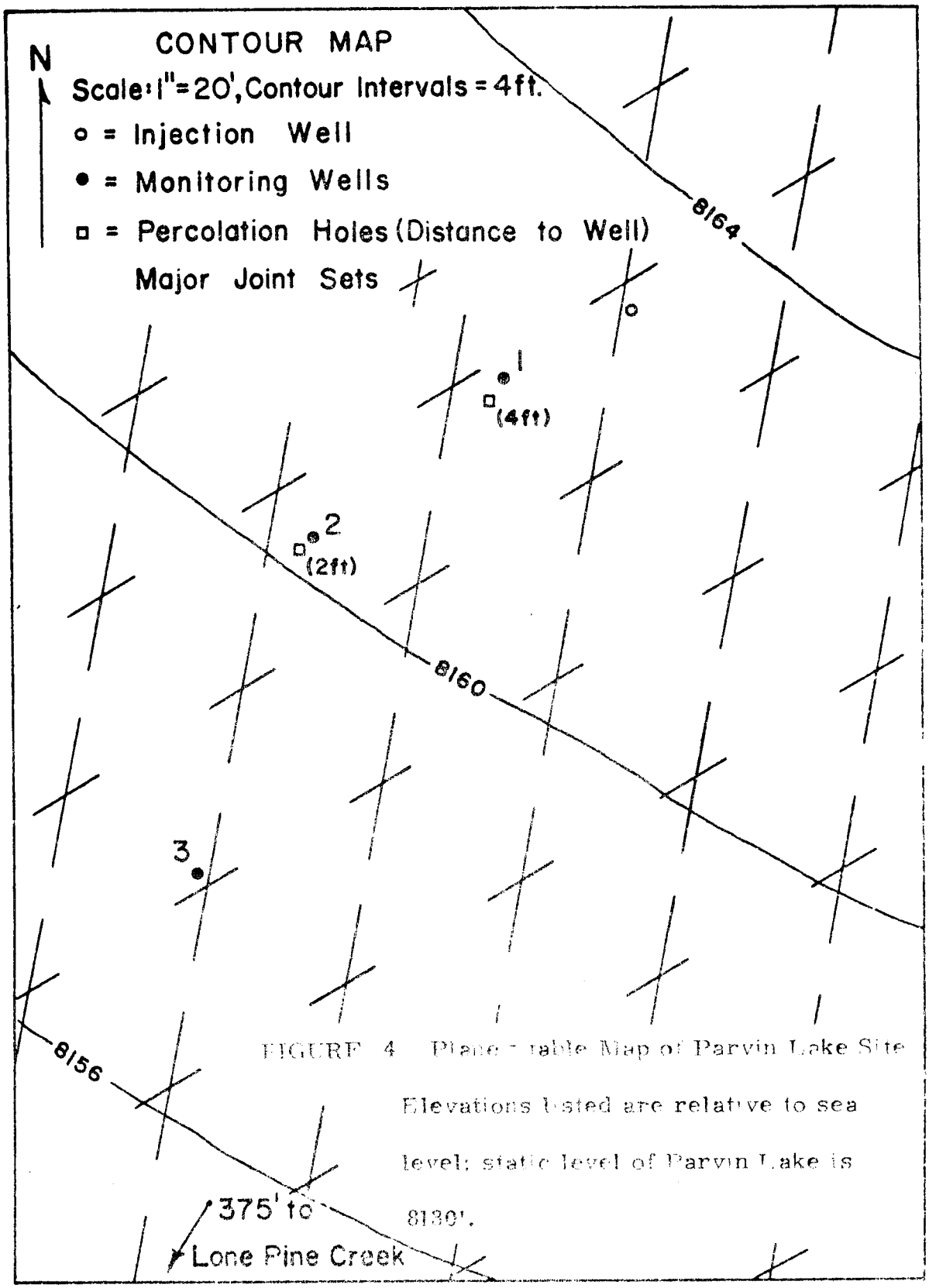


FIGURE 4 Plane-table Map of Parvin Lake Site

Elevations listed are relative to sea level; static level of Parvin Lake is 8130'.

PARVIN LAKE SITE

Parvin Lake which is 8130 ft. above sea level. Horizontal distances between the upper-most well (the injection well) and the three monitoring wells are 19, 51, and 95 ft.

3. Hydrogeologic Tests: Following drilling, the four wells were logged weekly with a neutron moisture probe (Well Reconnaissance, Inc., Dallas, Texas) to determine ambient water levels prior to microbiological testing. Depths to ground water were 26 ft. for the injection well, and 26 ft., 24 ft., and 18 ft. for the three monitoring wells (Figure 5). Caliper logs of the four wells did not reveal any demonstrable horizontal exfoliation fractures although adjacent rock outcrops indicated the contrary.

4. Inoculum: Bacillus stearothermophilis - American Type Culture Collection #7954 was the tracer bacterium used for injection tests in the zone of saturation. A lyophilized culture was suspended in Plate Count Broth (Difco Laboratories, Detroit, Mich.), streaked for isolation on Plate Count Agar (Difco), and incubated at 55 C for 18-24 hr. Isolated colonies were picked from the plate and restreaked to confirm culture purity.

Large numbers of the bacteria required for well injection were grown-up on half-strength Plate Count Broth (PCB). Ten one-liter flasks, each containing 500 ml of PCB were inoculated with the tracer bacterium and incubated in a Gyrotory shaker Model #G-25 (New Brunswick Scientific Co., New Brunswick, N. J.) at 55 C for

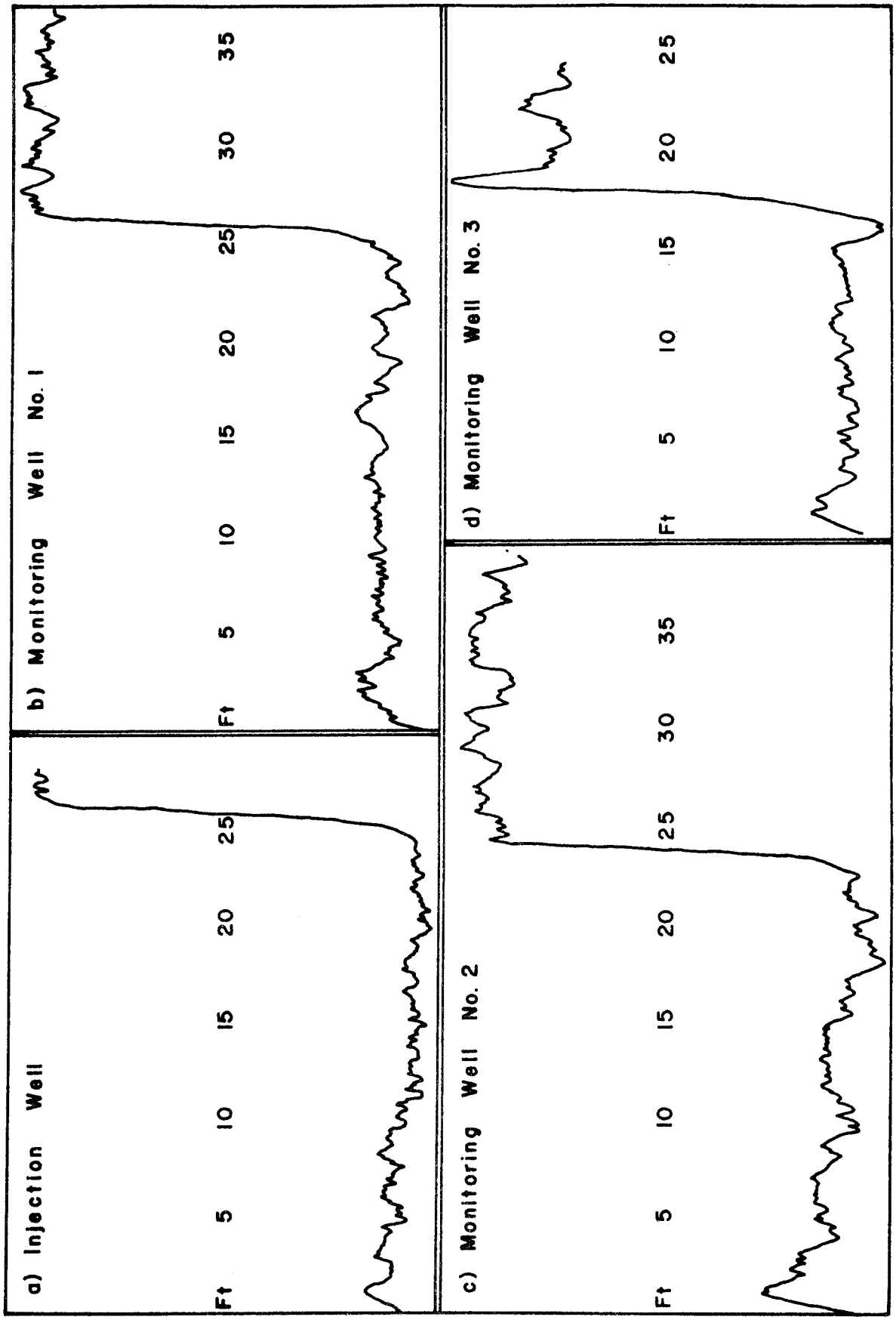
FIGURE 5. Neutron Logs of Parvin Lake wells; increasing depth is shown left-to-right; increasing moisture content is shown bottom-to-top.

a) Injection well, Time constant = 4 sec., sensitivity = 7.61, rate = 5 ft./min.

b) Monitoring well #1, Time constant = 4 sec., sensitivity = 7.61, rate = 5 ft./min.

c) Monitoring well #2, Time constant = 4 sec., sensitivity = 7.61, rate = 5 ft./min.

d) Monitoring well #3, Time constant = 4 sec., sensitivity = 7.61, rate = 5 ft./min.


a) Injection Well
b) Monitoring Well No. 1
c) Monitoring Well No. 2
d) Monitoring Well No. 3
Ft
5
10
15
20
25
30
35

36-48 hr; cell concentration after incubation was approximately 1×10^6 cells/ml. At the end of the incubation period, all inoculated flasks were aseptically transferred into a previously sterilized Pyrex carboy which was then stored under refrigeration until taken to the Parvin Lake site.

For the injection test, the desired inoculum was obtained by adding 500 ml of the laboratory-grown cell suspension into 55 gallons (208 l) of lake water. Final tracer bacteria concentration in the injection water was approximately $1\text{-}2 \times 10^3$ cells/ml. Into the uppermost well (the injection well), inoculated water was continually siphoned through 0.5" I.D. tubing for 36 hr. at an average rate of approximately one quart/min. The siphoning rate was regulated with adjustable hose clamps.

5. Microbiological Tests: Prior to the inoculation of the injection well with the tracer bacterium, each well and the lake water was sampled to determine thermophilic populations using the spread plate method.

Plates were prepared with Plate Count Agar according to Standard Methods (4). After the plates were poured and allowed to solidify, they were incubated 36-48 hr. at room temperature. Any contaminated plates were discarded with the remaining plates stored under refrigeration until needed.

Aliquots (0.1, 0.2, and 0.5 ml) of each source were added to the spread plates. The aliquot was then spread uniformly over the entire surface of the agar plate with a previously alcohol-dipped and flamed bent glass rod. After incubation at 60 C for 18-24 hr., plates were examined for numbers and types of thermophiles using a New Brunswick Colony Counter Model #C101 (New Brunswick Scientific Co.).

At six-hour intervals following the initial inoculation of the injection well, aliquots (0.2, 0.5 ml) from each of the three monitoring wells were analyzed using spread plates for increased numbers of thermophiles. Samples were obtained by lowering into each well a 100 ml dilution bottle suspended on a cable. The sampling bottle was alcohol-rinsed and thoroughly washed with sterile phosphate buffer before use to prevent inadvertent contamination of the monitoring wells with the sampling apparatus. In addition, monitoring wells farthest from the injection well were sampled first in order to minimize the possibility of introducing the tracer bacteria into the downslope wells during the sampling procedure rather than through ground water movement.

Each sample was plated immediately at the site in a camper-pickup truck equipped with laboratory apparatus. Incubation of the spread plates was at 60 C for 18-24 hr. All plates were counted after incubation for thermophiles and refrigerated until brought back

to the laboratory. Monitoring wells which yielded significant increases in thermophilic populations were sampled daily to ascertain the persistence of the tracer bacterium in the ground water.

Field thermophilic isolates from the monitoring wells were brought to the laboratory for further identification. Colonies were picked from the field spread plates and streaked for isolation. Three successive streakings were performed to insure culture purity. Biochemical and morphological characteristics of stock B. stearothermophilis and 10 field thermophilic isolates from the monitoring wells were compared to determine whether field isolates and the stock tracer bacterium were the same.

B. Bacterial Movement in the Zone of Aeration

1. Bacterial Movement through Metamorphic Bedrock

a. Site Location and Geologic Description: The Cache La Poudre River Canyon site is located 4 miles upstream from the junction (Ted's Place) of U. S. Highway #287 and Colorado State Highway #14 (Figure 6). The Poudre Canyon site consists of an abandoned road-cut made through a metamorphic rock formation (Figure 7). The bedrock is a weathered amphibolite containing hornblende, plagioclase, biotite and quartz. Weathering, which is most pronounced along the fractured surfaces has produced ferrous iron, some clay minerals and perhaps small amounts of carbonate

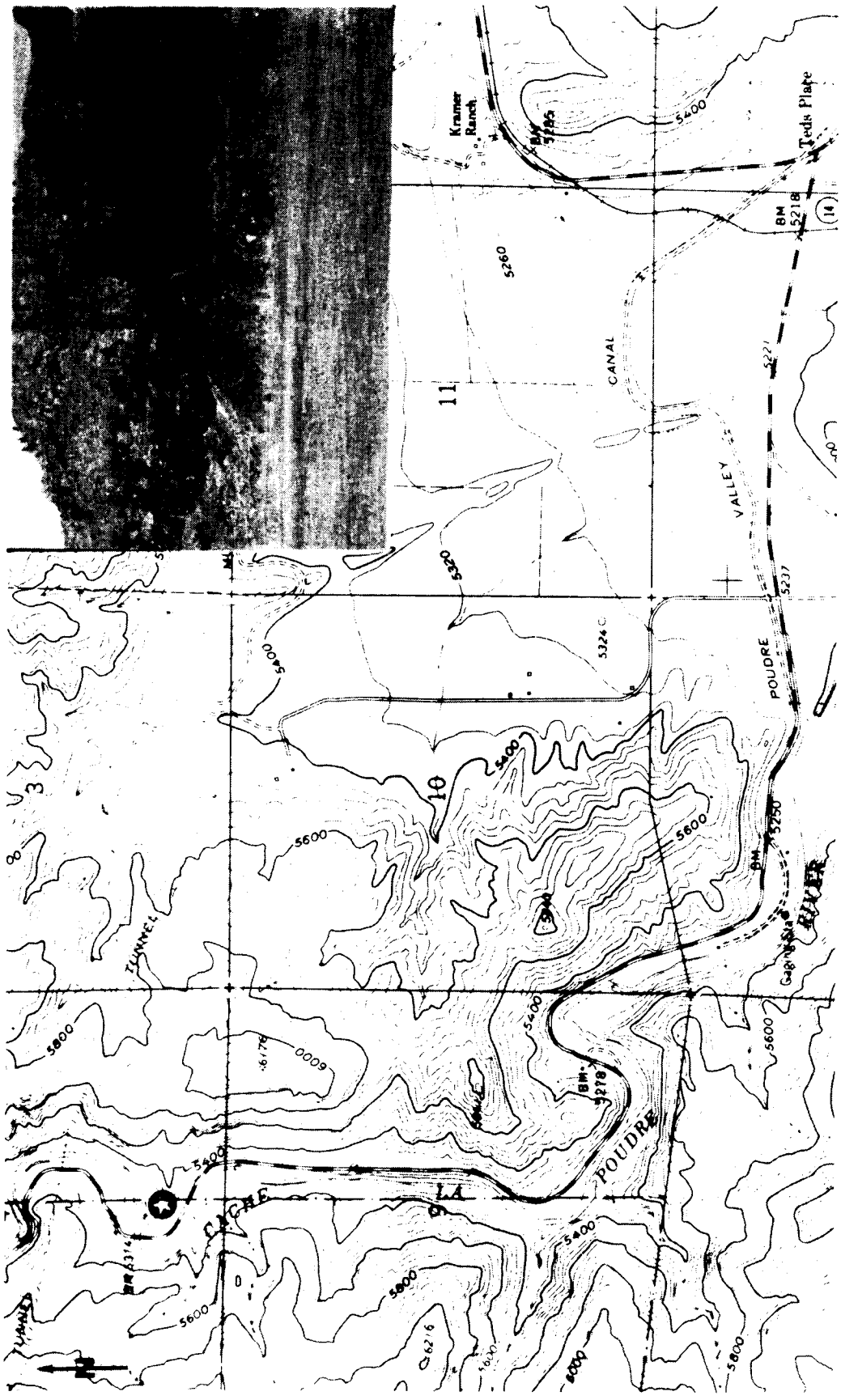


FIGURE 6. Cache La Poudre River Canyon Site Location: T8N, R70W, Section 4 Elevation: 5320'

Map taken from U. S. G. S. 7.5' Laporte Quadrangle (1962): Scale = 1:24000; Contour Intervals = 40'; Photo view toward the NNE.

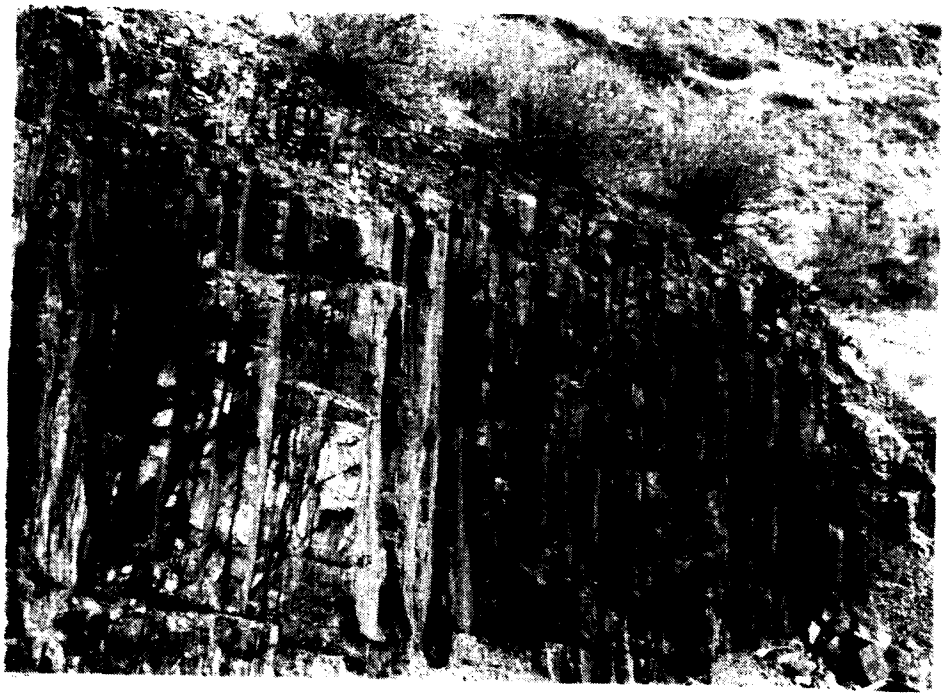
FIGURE 7. Photographs of Cache La Poudre River Canyon Site

A. West face of road-cut showing injection holes; arrows indicate joint set which dips 20-30° toward the southeast.

B. East face of road-cut showing vertical joint set; spacing of joints approximately 6-8 inches.

A

B



deposits. Coatings on the fractured surfaces appear to be the result of leaching of the thin soil mantle in incident precipitation.

At least two joint or fracture sets are present in these rocks. These joint sets are anisotrophic to percolating waters (Figure 2). The most prominent and regular joint set is the nearly vertical fracture set which has a strike of N35^{o}E. Average spacing of these fractures is approximately 6-8 inches (Figure 7). A second, irregularly spaced, set of fractures dips at approximately 20-30^{o} toward the southeast. This joint set is noted by arrows in photograph A of Figure 7.

b. Site Development: Seven percolation holes were developed on both sides of the road-cut and at varying levels above the bottom of the road-cut. The holes, 8-10 inches in diameter, were hand-dug to a depth of approximately 2 ft. below the soil-bedrock interface. Each hole was vacuumed to remove loose soil and fine rock particles. Following the addition of 1-2 inches of clean river gravel to the bottom of each hole, a 4 ft. length of 6-inch polyvinylchloride plastic pipe was permanently affixed to the underlying bedrock with 50 lbs. of mortar which was allowed to harden thoroughly. Thus, inoculated water introduced into the holes could only flow out of the encased holes via the fractures in the underlying bedrock. From seven holes developed, three were found to have

rapid infiltration rates with no appreciable leakage of water around the mortar seal and yielded water along the face of the road cut.

c. Hydrogeologic Test: Water required for both the microbiological and hydrogeological tests was obtained by pumping river water through garden hoses into 55 gallon storage drums situated next to the injection holes. Fluorescein-dyed water was siphoned into each of the three holes using 0.5 inch I. D. tubing until the dyed water emerged from various points along the face of the road-cut. Siphoning rates (4-20 gallons/hr) for each hole were metered using adjustable hose clamps. Points and elevations where the dyed water emerged as well as the position and elevations of the three injection holes were determined by plane-tabling (Figure 8). Times required for the dyed water to flow from the injection holes to the face of the road-cut were recorded. Extended injection tests, up to three hours, were performed to determine whether infiltration rates varied with time or if percolating waters emerged from additional fractures.

d. Inocula: For the microbiological test, river water was amended with non-chlorinated sewage effluent obtained daily from the Fort Collins municipal waste treatment plant. Prior to filling the storage drums, one gallon of sewage effluent was added to each drum. The river water and inoculum were thoroughly mixed prior to the percolation tests.

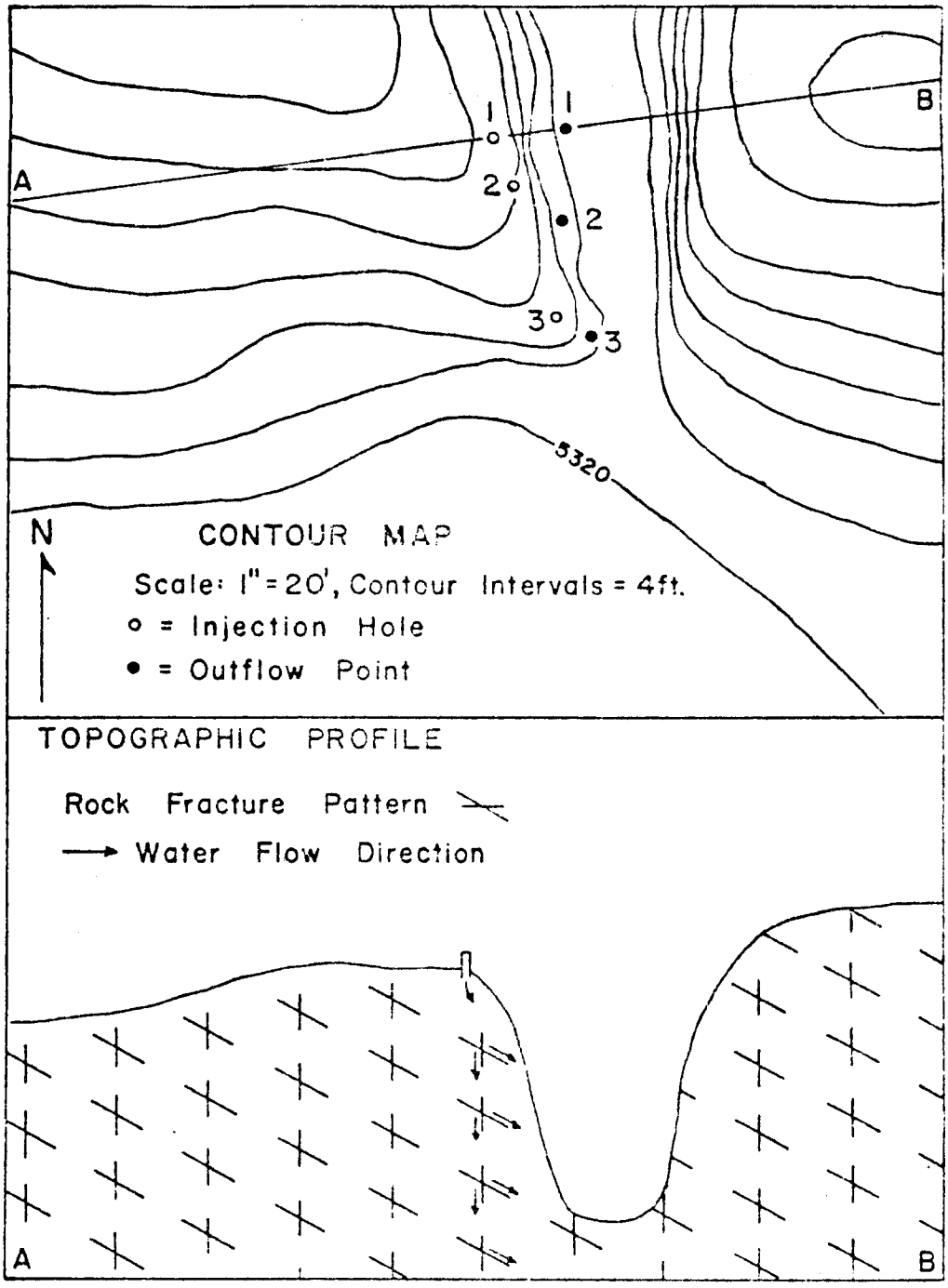


FIGURE 8. Plane-table Map and Topographic Profile of Poudre Canyon Site. Elevation below are relative to a fixed point not shown on contour map.

Injection Hole #1	25.87 ft.	Outflow Point #1	11.37 ft.
Injection Hole #2	23.79 ft.	Outflow Point #2	13.16 ft.
Injection Hole #3	19.22 ft.	Outflow Point #3	15.55 ft.

In one experiment, a tracer bacterium, Bacillus stearothermophilis was used as the inoculum instead of sewage effluent.

e. Sample Collection: Water samples were obtained from the inoculated river water prior to siphoning into the injection holes and from the water emerging from fractures along the face of the road-cut.

During injection of inoculated water from the storage drums into the test holes, samples were collected from the siphon hose in half-gallon, polyethylene, screw-cap containers. The samples were placed in the river to keep cool (average river temperature less than 10 C) during the time required to complete the percolation tests.

Water emerging from the face of the bedrock was collected by drilling 3/8 inch holes into the rock fractures and wedging a scoopula blade (Fisher Schietific Co., St. Louis, Mo.) into the holes. Samples were collected in 500 ml polypropylene bottles and brought directly to the laboratory for analysis.

f. Microbiological Procedures

(1) Plate Counts: Total viable bacterial counts of water samples obtained prior to percolation through the bedrock and on water which emerged from the fractured rock were determined using the spread plate method which has been previously presented in section A5 of the Field Procedures.

Serial dilutions of the water samples were made using 9 ml and 99 ml sterile phosphate-buffered water blanks. The phosphate buffer was prepared according to Standard Methods (4). Spread plates were made using the appropriate dilutions necessary to produce bacterial plate counts ranging between 30 and 300 colonies per plate. For each dilution, an 0.1 ml aliquot was added to each PCA plate. Spread plates were incubated for 36-48 hr. at 30 C and then counted using a New Brunswick Colony Counter Model #C101 (New Brunswick Scientific Co.)

Microbiological analysis of water samples containing the tracer bacterium, B. stearothermophilis was also determined by the spread plate method. Incubation was, however, at 55 C for 18-24 hr.

2. Bacterial Movement through Igneous Bedrock

a. Site Location and Geologic Description: The Parvin Lake area was chosen as the test site. The location and geologic description have been previously presented in section A1 of Field Procedures.

Hydrogeologically important at the Parvin Lake site is the highly decomposed, friable granitic "top soil" commonly termed gruss (Figure 9). This gravel-like material extends to depths ranging from 1-5 ft. and becomes progressively more consolidated with depth. At a depth of 15-17 ft., the bedrock appears to be quite fresh, i. e., has undergone little weathering.

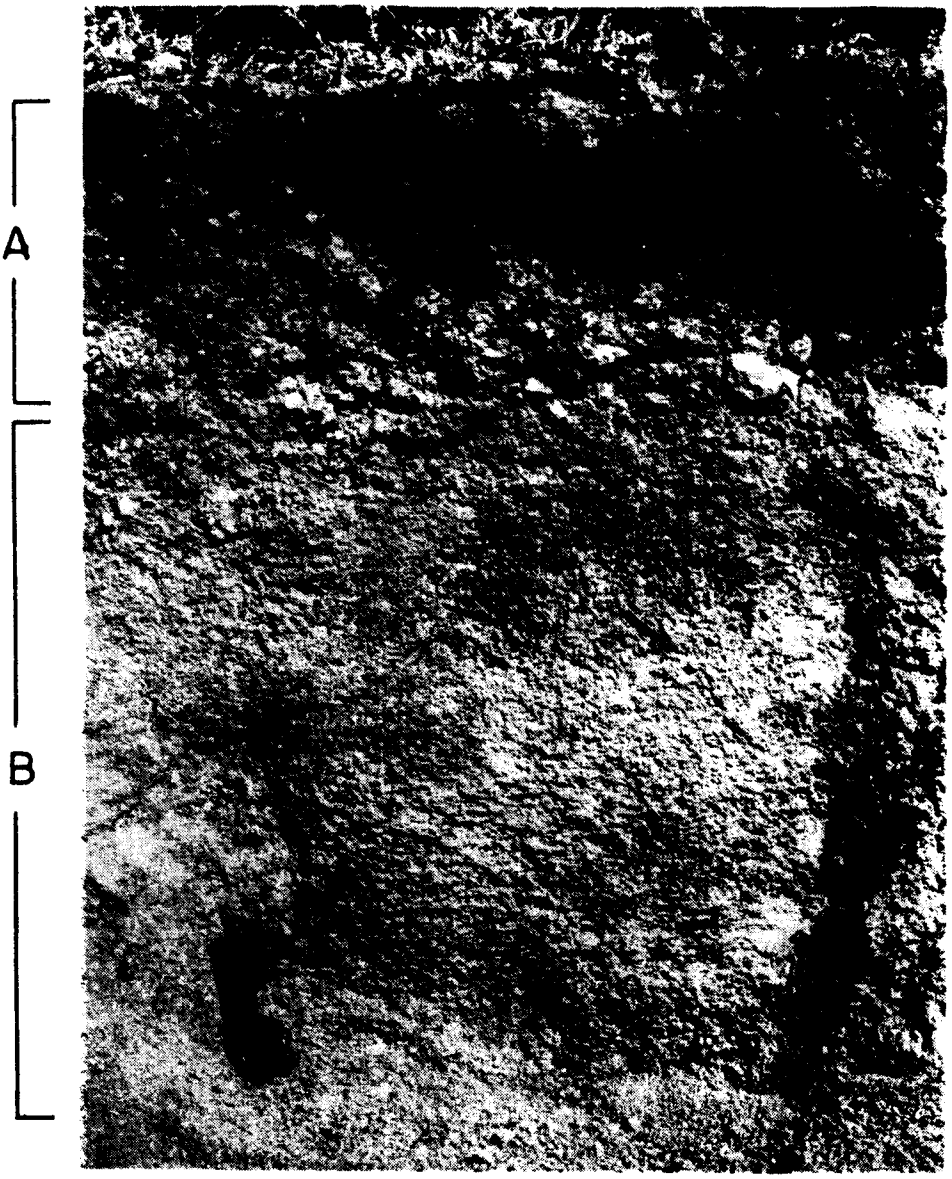


FIGURE 9. Soil profile at Parvin Lake site: "top soil" extends down to a depth of 8-10 inches with decomposed granite (gruss) extending to depths of 1-5 ft.

Soil Horizon A - litter layer, high organic matter content

Soil Horizon B - transitional layer; highly decomposed granite (gruss)

b. Site Development: Percolation holes, similar in construction to those at the Poudre Canyon site, were developed adjacent to monitoring wells #1 and #2 (Figure 4). Two percolation holes were established at horizontal distances of 2 ft. and 6 ft. from monitoring well #2 while a single hole was developed 4 ft. from well #1.

c. Hydrogeologic Tests: The existence of hydrologic connections between percolation holes was determined using fluorescein-dyed water and/or salt (sodium chloride) water. Tracer water was siphoned from storage drums into the percolation holes at a rate of 1-2 quarts/min. Monitoring wells were sampled every 15 minutes for the arrival of the tracer water in the adjacent well by lowering a sampling bottle suspended from a cable. Presence of fluorescein in the well water was determined by visual inspection while increased salt content was ascertained with a Model RA-2A conductivity meter (Industrial Instruments, Cedar Grove, N. J.). Ambient conductivity of the ground water was determined prior to hydrologic testing.

d. Inoculum: Bacillus stearothermophilis was used as the tracer bacterium. Cultural and inoculation procedures have been previously described in section B4 of Materials and Methods.

e. Microbiological Tests: Percolation holes which yielded fluorescein or salt water to the adjacent monitoring wells

were inoculated with tracer bacteria by siphoning. Sampling procedures and microbiological enumeration of the well-water has been previously described in section B5.

II. Laboratory Procedures

A. Rock Sample Preparation: Representative rock samples of differing composition and textures were collected to determine whether bacteria present in percolating water could be effectively removed either by toxic compounds released by the geological material or physical absorption by mineral crystals. Thirty (30) rock samples (Appendix, Tables 6A, 6B) and their respective chemical analysis (Appendix, Tables 7, 8) were obtained form Dr. M. E. McCallum, Department of Geology, Colorado State University. Rock samples were crushed with a jaw crusher (Denver Fire Clay Co., Denver, Colorado) and sieved to produce aggregates of uniform surface area. Sieve sizes used were Nos. 10, 12, 14, 16, and 18 of the U. S. Standard Sieve Series (W. S. Tyler Co., Cleveland, Ohio). All rock samples were rinsed briefly with deionized water to remove any residual dust left from the crushing operation and dried at 105 C. Samples were stored in 18 oz. Whirl-Pak plastic bags (Scientific Products, Evanston, Illinois).

In addition to the rock samples, a very pure quartz sample was used throughout the laboratory studies as a control. The control was prepared identically to the other 30 samples.

B. Aggregate Preparation: Into 250 ml, screw-cap, Erlenmeyer flasks, a volume of 50 cm^3 of each rock sample was added plus 100 ml of distilled water. The rock-water mixtures were stored at 20 C for 72 hr. to allow for pH equilibration. Determinations of pH were made prior to inoculation of bacteria to the rock-water mixtures and at the end of 21 days to determine whether the pH changed appreciably during the laboratory studies.

Some of the rock samples obtained were not tested due to the lack of sufficient quantities after the crushing process.

C. Inoculum: A wild strain of Escherichia coli was grown-up in a Model #G-25 Gyrotory shaker (New Brunswick Scientific Co.) for 24 hr. at 37 C in four-250 ml Erlenmeyer flasks containing 100 ml of half-strength Plate Count Broth (Difco). Following incubation, the contents of the four flasks were centrifuged using a Sorvall RC-2 (Ivan Sorvall Co., Norwalk, Conn.). Cell pellets were re-suspended in sterile phosphate buffer. The centrifugation and washing procedures were repeated two more times.

The washed cell-suspension was diluted with sterile phosphate buffer to an optical density of 0.15 at 450 nm determined with a Spectronic 20 (Bausch and Lomb, Rochester, N. Y.). This dilution resulted in a cell density of approximately 7×10^7 cells/ml.

Each rock-water mixture was inoculated with 1.0 ml of the diluted cell-suspension. Flasks were hand shaken to disperse the bacteria

and stored at 20 C. Also, a flask containing only 100 ml of distilled water was inoculated as a control.

D. Microbiological Tests:

1. Initial Cell Counts

Immediately after inoculation of all the rock-water samples, initial cell counts were determined by: 1) the spread plate method (See section A6a of Field Procedures) and 2) the membrane filter procedure (See section A6b of Field Procedures).

2. Daily Cell Counts

Coliform counts on all the rock-water samples were performed every 24 hr., at first, using the membrane filter procedure. Following 7-10 days of daily testing, samples were analyzed every 2 or 3 days.

E. X-ray Diffraction Analysis: After extended exposure (3-4 weeks) of the rock aggregates to water, most of the samples produced appreciable amounts of clay-like material. In order to determine whether the differing bacterial die-off rates were due, in part, to the formation of clay minerals, the "fines" from each of the samples were analyzed for the presence of clay minerals using X-ray diffraction (Performed at the Department of Geology, Colorado State University).

Each sample was first shaken to disperse the "fines" and then allowed to stand undisturbed for several minutes to remove any fine

rock fragments present. An aliquot of the slurry was then placed in an evaporating dish and allowed to air-dry for several days. The dried sample was then pulverized in a porcelain mortar prior to X-ray analysis.

Whenever possible, an attempt was made to identify the clay type in each sample. The presence and type of clay minerals found in the various rock samples were compared with their respective die-off rate.

F. Additional Microbiological Tests: A number of the rock samples were inoculated a second time (second exposure) to determine whether similar die-off rates could be obtained; exposure of the fresh rock to water and the subsequent production of clay-like materials may have appreciably altered die-off rates produced by the rock types after the first inoculation.

Rock samples used in the first exposure were rinsed thoroughly and dried at 105 C. Inoculation procedures and bacterial analysis were identical to those described in sections C, D1, and D2 of the Laboratory Procedures.

Three clay types, montmorillonite, illite, and kaolinite, were also examined to determine their effect upon bacterial longevity. A 1.0 g sample of each clay type was added to a 250 ml Erlenmeyer flask containing 100 ml of distilled water. The three flasks were inoculated with a 1.0 ml cell-suspension of E. coli (See Section C of

Laboratory Procedures), hand shaken to disperse the inoculum, and stored at 20 C. Daily cell counts were made on the inoculated clays using the membrane filter procedure.

G. Statistical Analysis: A statistical correlation between the varying chemical constituents of the rock samples and die-off rates was made to determine whether an element or group of elements could account for some of the variability in bacterial survival. Included in the analysis were silicon, calcium, sodium, aluminum, iron, magnesium, titanium, phosphorous, manganese, and potassium. Data for trace elements were available for only a few rock samples and therefore were not included. The differing pH values produced by the rock samples were also included in the statistical analysis.

Analysis was obtained from a multiple step-wise regression and correlation computer program with graphic output for model evaluation.

RESULTS

Results of this study are presented as follows: 1) bacterial movement through fractured bedrock in the zone of saturation, 2) bacterial movement through fractured bedrock in the zone of aeration, and 3) geochemical effects on the survival of fecal-type bacteria.

Bacterial Movement through Fractured Bedrock in the Zone of Saturation

Data obtained at the Parvin Lake site in granitic igneous rock are presented in Table 1. Thermophilic populations in the three monitoring wells are extrapolated from 0.2 ml aliquots. Thermophilic isolates from monitoring wells #1 and #2 produced morphologically different colonies on PCA than those typically produced by the tracer bacterium.

Spread plates from monitoring well #3, which contained a high number of typical tracer-like colonies (24, 30, and 36 hr. samples) were brought to the laboratory to establish whether these thermophilic bacteria were the same organisms added to the system and transported by ground water movement from the injection well. Biochemical and morphological characteristics of stock Bacillus stearothermophilis and 10 field isolates are presented in Table 2. Although dilution of the inoculum by the ground water precludes any

TABLE 1. Thermophilic populations (numbers/ml) of monitoring well-waters during and after 36 hr. inoculation of the injection well (Parvin Lake Site).

Time (hr.)	Monitoring Well 1	2	3
0	0	10	0
6	0	0	—
12	5	0	—
18	0	0	10
24	5	0	140
30	10	5	115
36[1]	0	5	65
48	0	5	60
72	—	—	60
96	—	—	55
120	—	—	65
144	—	—	10
164	—	—	0

[1] Inoculation of injection well terminated

TABLE 2. Biochemical and Morphological Characteristics of Bacillus stearothermophilis and ten field isolates from monitoring well #3.

Characteristic	Bacillus stearothermophilis	Isolates
Growth at 65°C	+	+
Growth at 70°C	-	-
Gram reaction	variable	variable
Citrate utilized	-	-
Aerobic	+	+
Colony morphology	yellow, smooth, raised	yellow, smooth, raised
Cell morphology	long, thin rods	long, thin rods
Spores	terminal	terminal
Indole production	-	-
Acetylmethylcarbinol production	-	-
Starch hydrolyzed	+	+

quantitative results, it is clear from the above results (Table 1 and 2) that the tracer bacterium traveled through the zone of saturation a distance of 94 ft. in 24-30 hr.

Additional sampling of the monitoring well #3 showed the tracer thermophiles to be present in this well for a least six days after initial inoculation of the injection well (Table 1). The fact that tracer thermophiles were never recoverable from monitoring wells #1 and #2 is thought to be due to the orientation of the rock fractures (Figure 4) directing the flow of tracer waters away from these wells and the direction of the local ground water gradient at the Parvin Lake site which is predominately north to south.

Bacterial Movement through Fractured Bedrock in the Zone of Aeration

A. Bacterial Movement through Metamorphic Rock (Poudre Canyon site).

Microbiological and hydrological results obtained from the Poudre Canyon site are presented in Table 3. The majority of the percolation tests were conducted using injection hole #1 since this hole produced a larger horizontal (8 ft.) and vertical (14.5 ft.) displacement of the inoculated waters than injection holes #2 or #3.

Total viable counts made on waters emerging from the face of the road-cut were generally higher than the viable counts on the inoculated waters prior to percolation through the fractured bedrock.

TABLE 3. Bacterialogical Analysis of Inoculated Waters used in percolation tests at the Poudre Canyon site.

Hole No.	Percolation Time[4]	Inoculum	Bacterial Total Counts/ml.	Coliforms/100 ml.	Fecal Coliforms/ ml.
1	14-25 min.	River water	Before[1] 4600	Before 120	—
			After[2] 2500	After 10	—
		River water	Before 1700	Before 50	—
			After 5000	After 20	—
		River water	Before 700	Before 60	—
			After 21000	After 16	—
		River water	Before 1200	Before 60	—
			After 2000	After 40	—
		River water	Before 1300	Before 40	—
			After 1400	After 20	—
		River water	Before 19000	Before 55	
			After 71000	After 52	—
		River water and effluent	—	Before 27000	—
			—	After 2300	—

TABLE 3. Continued

Hole No.	Percolation Time[4]	Inoculum	Bacterial Total Counts/ml.	Coliforms/100ml.	Fecal coliforms/100 ml.
1	14-25 min.	River water	—	Before 53000	Before 29000
		and effluent[5]	—	After 17000	After 13000
		B. stearothermophilis and river water	Before[3] 7700 After 6800	— —	— —
2	10-16 min.	River water	Before 1200 After 1600	Before 40 After 35	— —
3	8-10 min.	River water	Before 13300 After 8600	Before 20 After 104	Before 16 After 60

[1] Bacterial analysis on water being siphoned into injection holes

[2] Bacterial analysis on water which emerged from the fractured bedrock

[3] Incubation at 60 C for 18-24 hr.

[4] Based on a percolation rate of approximately 5 min./inch (6 gallons/hr.)

[5] Siphoning rate adjusted to 7 min./inch (4 gallons/hr.)

In two percolation tests, total viable counts were less after emerging from the face of the road-cut. In both of these tests, however, it was the first time inoculated waters were siphoned into two of the injection holes. In addition, spread plates inoculated with the first water emerging from the fractured bedrock contained a large number of mold spores. These spores are presumed to have been flushed from the surfaces of the rock fractures by the percolating waters. Subsequent percolation waters did not contain appreciable numbers of mold spores.

The enumeration of coliforms present in both the injection water and percolating water showed that there was a decrease in coliform densities as a result of water flowing through the bedrock (Table 3). These differences in coliform numbers were not considered significant since the river water contained relatively few coliforms. For this reason, two percolation tests were made using river water amended with sewage effluent to substantially increase coliform densities. Fecal coliforms were also analyzed in one of the above percolation tests. In an additional test the tracer bacterium, B. stearothermophilis, was inoculated into the river water. Percolating waters were collected and the thermophilic populations enumerated by high temperature (60 C) incubation of spread plates. Results of these studies are presented in Table 3.

B. Bacterial Movement through Igneous Rock (Parvin Lake site).

Bacterial movement through the zone of aeration was determined by siphoning water containing B. stearothermophilis into shallow 2 ft. injection holes located approximately 2 ft. from monitoring well #2, and 4 ft. from monitoring well #1. The inoculated water also contained fluorescein dye.

Following the addition of 20-25 gallons of tracer water into the injection hole adjacent to monitoring well #2, fluorescein-dyed water was present in the well-water. Bacterial analysis revealed the tracer bacteria to be present also in the well-water. Approximate travel time for the percolating water was 10-15 min. The tracer water entered the well above the zone of saturation and trickled down the inside of the well. Similarly, tracer waters added to the injection hole located 4 ft. from monitoring well #1 were also found in the well-water. Percolation time for the tracer water was less than two hours. This rather long travel time is thought to be due, in part, to the slow infiltration rates encountered at this particular injection hole.

While the horizontal distances between the injection holes and their respective monitoring well were very short (2 and 4 ft.), the above results do show that waters, such as leachfield effluent, can percolate through the zone of aeration and possibly enter adjacent well-water supplies. Depending upon the depth of the well, rock

fracture characteristics, distance between the domestic waste disposal unit and well, and drawdown properties of the well, leach-field effluent could enter ground water supplies and pose a health hazard.

Geochemical Effects on the Survival of Fecal-type Bacteria

The variable geochemical effects upon bacterial survival are presented in Table 4. Bacterial die-off rates (slopes) are expressed as the $-\log_{10}$ decrease in coliforms per day. The term "first exposure" refers to the first inoculation of a laboratory strain of Escherichia coli into the rock-water aggregates. Initial coliform concentrations of the rock-water mixture were 6.0×10^5 cells/ml for the first exposure and 1.3×10^6 cells/ml for the second exposure. Prior to the inoculation of these aggregates a second time (second exposure), the "fines" were removed, as described in section E of Laboratory Procedures (Materials and Methods), for X-ray analysis for the presence of clay minerals (Table 5). Die-off rates for each sample were obtained from a computer-generated best-fit line based on the daily coliform determinations.

From Table 4 and Figures 10 and 11, it can be seen that while several rock samples produced rapid die-off rates, i. e. samples E1, L1, D2, E2, quartz, etc., the majority of the rock types tested had a negligible effect on bacterial survival. It is also interesting to note that following a second inoculation of E. coli to the same

TABLE 4. Variable Geochemical Effects on Bacterial Survival expressed as $\log_{10}$ decrease in coliforms/unit time (day).

Sample No.	First Exposure	Second Exposure	Sample No.	First Exposure	Second Exposure
A1	-0.023	-0.011	A2	-0.008	-0.006
B1	-0.021	-0.101	B2	-0.016	-0.021
C1	-0.016	-0.059	C2	-0.016	-0.006
D1	-0.117	-0.014	D2	-0.752	-0.014
E1	-0.379	-0.019	E2	-1.014	-0.076
F1	-0.010	-0.004	F2	-0.005	-0.070
G1	-0.084	-0.034	G2	-0.048	-0.187
H1	-0.115	-0.116	H2	-0.096	-0.025
I1	-0.006	-0.003	I2	-0.059	-0.089
J1	-0.014	-0.113	J2	—*	-0.064
K1	-0.009	-0.009	K2	-0.123	-0.007
L1	-0.354	-0.091	L2	-0.005	-0.088
M1	-0.256	-0.071	M2	+0.001	-0.096
Qtz	-0.444	-0.662	N2	-0.048	-0.014
Blk	—	-0.116	O2	-0.499	-0.119
			P2	-0.069	-0.103
			Q2	-0.108	-0.122
			Qtz	-0.628	-0.113
			Blk	—	-0.116

*Insufficient sample for testing

TABLE 5. X-ray Diffraction Analysis on "Fines" obtained from Selected Rock Samples after First Exposure.

Sample No.	Clay Type	Rating (1-10)	Sample No.	Clay Type	Rating (1-10)
A1	amorphous	--	A2	montmorillonite	7
B1	--	--	B2	amorphous	--
C1	amorphous	--	C2	illite	5
D1	amorphous	--	D2	amorphous	--
E1	amorphous	--	E2	montmorillonite	4
F1	montmorillonite	9	F2	--	--
G1	illite	3	G2	--	--
H1	amorphous	--	H2	--	--
I1	illite	1	I2	montmorillonite	6-7
J1	--	--	J2	montmorillonite	2
K1	--	--	K2	--	--
L1	kaolinite	2-4	L2	--	--
M1	--	--	M2	illite	7
N1	amorphous	--	N2	illite	2-3
			O2	--	--
			P2	--	--
			Q2	illite	5

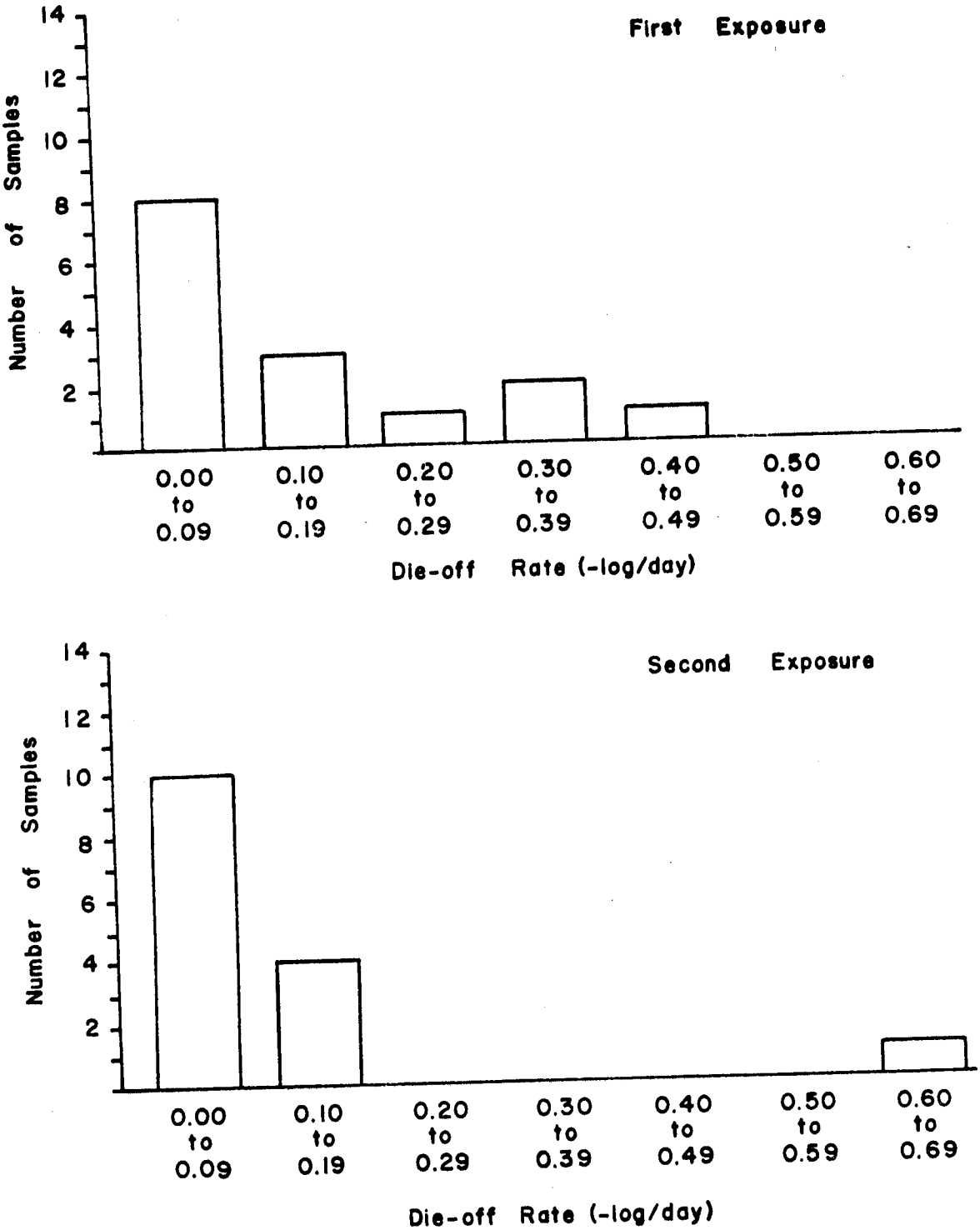


FIGURE 10 Variable Geochemical Effects on Bacterial Survival; Distribution pattern of die-off rates of coliforms exposed to rock samples A1 through M1 and quartz (Taken from Table 4).

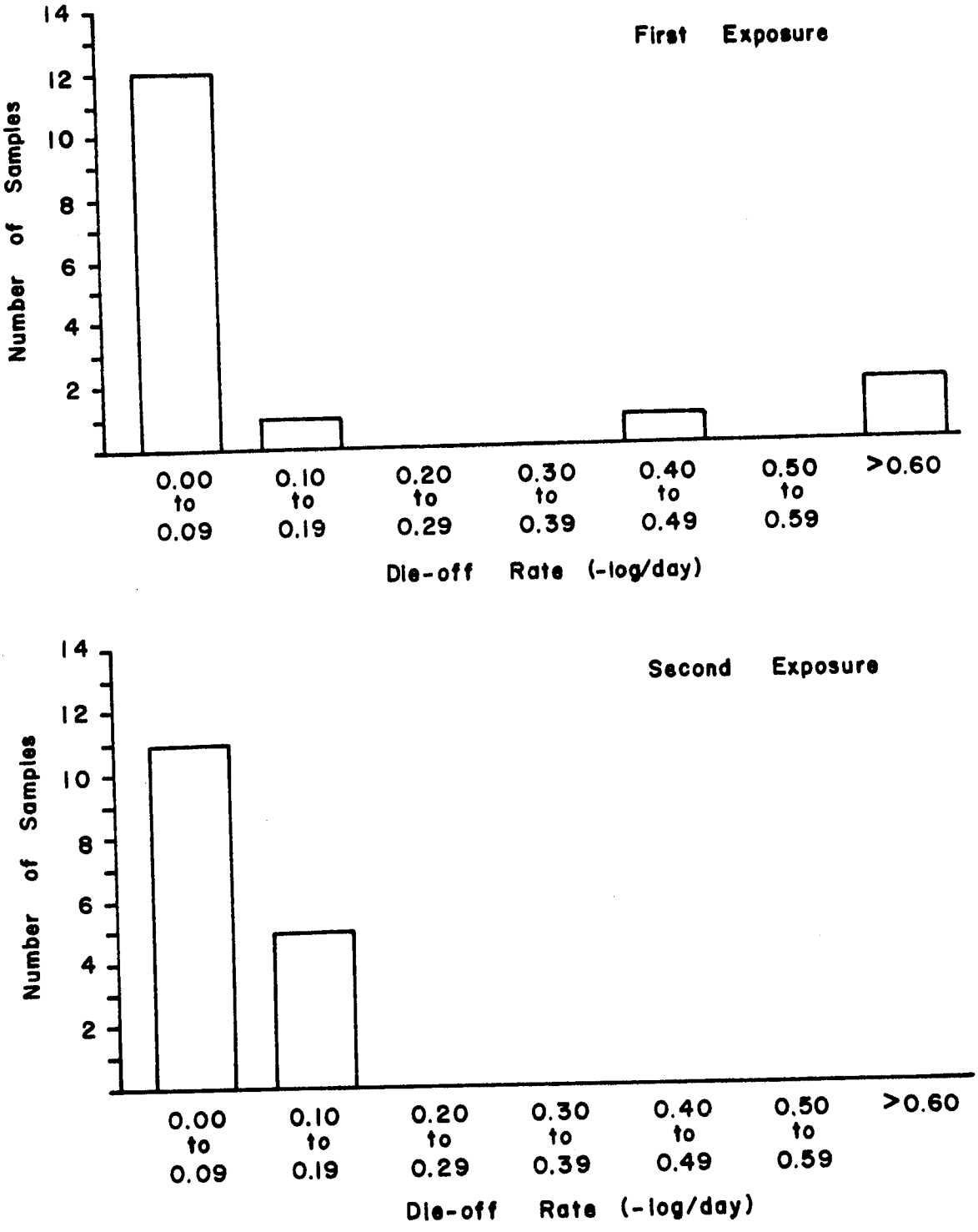


FIGURE II Variable Geochemical Effects on Bacterial Survival; Distribution pattern of die-off rates of coliforms exposed to rock samples A2 through Q2 and quartz (Taken from Table 4).

rock-water aggregates, die-off rates decreased or remained approximately the same as rates obtained from the first exposure (Figures 10 and 11).

X-ray diffraction analysis of the "fines" generated during the first exposure were performed to determine whether the differing survival rates were a function of clay mineral formation (Table 5). From twenty (20) samples analyzed, eight were found to possess an amorphous diffraction pattern (no clay minerals). The remaining 12 samples contained montmorillonite (5 samples), illite (6 samples), and kaolinite (1 sample). Further, those samples which contained clay minerals were rated upon their respective X-ray diffraction pattern on a scale of 1 to 10 with a rating of 10 indicating a high degree of crystallinity (clays) being present in the "fines". A comparison between the variable die-off rates and the presence (rating) or type clay did not reveal any correlations. Additional laboratory studies in which E. coli was inoculated into three relatively pure clay slurries (kaolinite, illite, montmorillonite) showed that clay minerals do not effectively produce rapid bacterial die-off rates although clays are effective in bacterial and viral absorption (15).

A step-wise regression analysis on the varying chemical constituents of the rock samples found only silicon, sodium, and calcium to account for most of the variation related to bacterial

die-off rates. These elements are important constituents of silica and feldspars. Calcium and sodium are found mainly in plagioclase feldspars. These minerals break down readily upon hydration to produce secondary clay minerals.

An analysis of variance of the regression showed that the model which included these three variables (silicon, sodium, and calcium) demonstrated greater than 95% significance.

DISCUSSION

The purpose of this investigation was to document the direction and rate of movement and the survival of bacteria added to ground waters percolating through various types of fractured bedrock. Bacteria-laden waters were introduced into differing rock strata at rates and depths similar to those encountered in the leachfields of conventional waste disposal systems. From this study, guidelines presently used in determining the suitability of mountain building sites for installation of septic-tank soil-absorption units were evaluated. Criteria which have been employed in determining the acceptability of a site for disposal of domestic wastes include minimum distances between leachfields and water-wells, percolation tests, and depth of soils beneath the proposed leachfield.

Characteristically, effluent entering a leachfield from a properly designed and maintained septic tank contains relatively little suspended solids, but is typically high in dissolved materials, both organic and inorganic, and microbial numbers. Thus, septic-tank effluent requires further chemical and microbial purification before it can be considered safe to re-enter ground water supplies. While domestic waste disposal systems are relatively inefficient in comparison to municipal waste treatment systems, the ground water quality is generally maintained by: 1) large horizontal distances

between water-wells and waste disposal sites, 2) consistently small quantities of waste produced in year-around family residences, 3) characteristically level topography in rural and urban areas, and most important, 4) the generally high filtration capabilities of soils underlying the leachfield.

In some mountain areas, septic-tank soil-absorption systems have been found to be inadequate in effectively filtering domestic waste waters, resulting in the contamination of numerous water-wells (12, 26). In one mountain community, over 60% of domestic wells tested were found to contain appreciable numbers of coliforms; approximately 16% of the wells tested had coliform densities greater than 100/100 ml. The source of this well-water contamination has generally been assumed to be septic-tank effluent entering inadequate leachfields and subsequently the ground water body, and, to a lesser extent, induced infiltration of contaminated surface waters into underlying fluvial deposits by excessive pumping. Prior to this investigation, little information concerning the movement of bacterial pollutants in crystalline rock terrains was known (31).

Typically, mountain dwellings are constructed along water courses or on sloping terrain where the absence of deep soil profiles and the highly fractured nature of the underlying bedrock contribute significantly to the possibility of microbial contamination of shallow ground waters. Purification of septic-tank effluent is most effective

in soils containing a high percentage of clay minerals (large surface areas); mountain building sites are usually devoid of clay soils. At the Poudre Canyon site (Figure 7), only a relatively thin veneer of soil covers the bedrock, while the top soil at the Parvin Lake site extends only to a depth of 8-10 inches; beneath the soil at Parvin Lake is several feet of highly weathered and porous granite (Figure 9).

Areas, such as abandoned stream channels or stream terraces, may contain fluvial or colluvial deposits with adequate amounts of soil and clay present to effectively filter microorganisms. More common along river and stream valleys, however, are the poorly-sorted river deposits of sand and gravel. Such deposits may produce highly productive water-wells and rapid infiltration of septic-tank effluent, but also result in little, if any, filtration of percolating effluent prior to entering ground waters and adjacent surface waters. In Colorado, as well as other Rocky Mountain states, where a majority of Front Range municipalities depend upon mountain streams for water supplies, uncontrolled development of mountain residences and communities along such water courses may result in the deterioration of surface water quality if present waste disposal methodology is not re-evaluated.

Under current design practices, effluent distribution tiles are installed at a minimum depth of 18 inches to prevent freezing and percolation of the effluent to the surface. At a large percentage of

mountain building sites, this depth requirement results in the absence of sufficient soils below the tiles to effect effluent purification, and, in many cases, places leachfield trenches directly on or in close proximity to bedrock fractures. At the Poudre Canyon site, such a requirement would place drain tiles directly into the fractured bedrock, while at Parvin Lake tiles would be set into the highly porous gruss.

An additional requirement for site approval is a minimum of 4-6 ft. of soil beneath the bottom of the tiles of an absorption field (6, 37). This regulation precludes the installation of soil-absorption systems in terrains such as the Poudre Canyon site, yet allows for leachfields to be installed in areas in which soil depth is sufficient but still inadequate to purify percolating effluent. At the Parvin Lake area, soils which are composed mainly of weathered granite, extend to depths greater than the required 4-6 ft., but are too coarse and porous to effectively purify percolating effluent before it enters the ground water.

Crystalline metamorphic (Poudre Canyon site), igneous (Parvin Lake site), as well as some sedimentary rocks, are commonly fractures or jointed. This fracturing is most pronounced near the soil-bedrock interface (8). In addition, the majority of bedrock fractures possess a regular orientation, i. e., dip, strike, density (Figures 2, 4, and 7). Thus the movement of effluent which has entered underlying bedrock via fractures may be controlled

considerably by the fractures in the confining rock stratum. Geologic units in which the fracture orientations or other rock structures control the direction of ground water flow are commonly termed anisotropic.

At the Parvin Lake site, water inoculated with a tracer bacterium, Bacillus stearothermophilis, was used to determine both the rate and direction of contaminated ground water as well as the degree of anisotropy imparted to ground water movement by the major rock joint sets (Figure 4). The tracer bacterium, B. stearothermophilis, was chosen since: 1) appreciable numbers of thermophiles were not detectable from any of the four wells or lake water prior to inoculation of the injection well, 2) this organism can easily be grown in large quantities, 3) thermophiles are easily recovered using high incubation temperatures, 4) the organism is long-lived under field conditions, and 5) the organism is not pathogenic.

During and after the inoculation of the injection well, tracer waters were never recoverable from monitoring wells #1 and #2 (19 and 32 ft. from the injection well) although tracer bacteria were isolated from monitoring well #3 (Tables 1 and 2), 94 ft. from the injection well (Figure 4). The inability to isolate tracer thermophiles from the two nearer monitoring wells was thought to be the result of the anisotropic nature of rock permeability at this site

which controls the direction of both ground water flow and any contaminants present in the ground water.

It is also interesting to note the relatively rapid ground water velocities encountered in some mountainous terrains. At the Parvin Lake site, tracer bacteria traversed a horizontal distance of 94 ft. in 24-30 hr. (Table 1). From these data, it appears that adjacent water-wells up to several hundred yards away from a conventional waste disposal unit may be subject to contamination within a short period of time. It can also be seen in Table 1 that tracer bacteria were only present in monitoring well #3 for approximately 5 days after the inoculation of the injection well had been terminated. It appears that while rapidly moving ground waters can readily transport contaminants into near-by water-wells, the elimination of the source of contamination along with the flushing and dilution ability of ground waters seem to decontaminate these same wells within a relatively short period of time.

More important, data obtained at the Parvin Lake site by using tracer bacteria in the zone of saturation definitely show that microbial contamination originating from septic-tank effluent could readily move distances greater than 100 ft. Thus, present guidelines (6, 37) which recommend minimum distances of 50 or 100 ft. between water-wells and waste disposal sites or 50 ft. from any water course cannot be considered adequate to protect ground

water quality in geological formations similar to the Parvin Lake site. These minimal distances were, of course, established before the travel of pollutants in such terrains had been examined. Current guidelines also include a minimum vertical distance between the bottom of the leachfield and ground water tables, rock formations, or other impervious strata (6, 37). In this context, bedrock is considered to be impervious to septic-tank effluent, although this is not the case in some igneous and metamorphic rock formations (Table 1 and 3). At both test sites, the underlying bedrock readily accepted inoculated waters at rates (gallons/hr.) greater than those generally produced by septic-tank soil-absorption systems.

In addition to the required horizontal distances and depth of soils, the suitability of building sites for the installation of most domestic waste disposal systems is based almost entirely on standard percolation tests (rates). Such tests when conducted properly in non-mountainous terrains, provide useful, although minimal, data as to the absorption/filtration capabilities of the underlying soils. The main objective of percolation tests is to determine required absorption areas, i. e., how large the leachfield must be in order to accept and filter the daily volume of septic-tank effluent efficiently. In general, percolation rates are determined by digging a hole approximately the depth of the proposed leachfield trenches, adding water to the hole which has several inches of clean

gravel on the bottom, and recording the time (minutes) required for the water to drop one inch.

Regulations (6) state that building sites which produce percolation rates greater than 30 min/inch or less than 5 min/inch are not suitable for the installation of soil-absorption units. In mountain areas, farily rapid percolation rates (less than 10 min/inch) are commonly encountered at many building sites. While it is assumed that "perc" rates less than 5 min/inch are associated with insufficient filtration of septic-tank effluent, acceptible rates at the lower end of the 6-30 min/inch range cannot be equated with adequate effluent filtration as evidenced at the Poudre Canyon site (Table 3).

The siphoning of inoculated waters into hole #1 at permissible percolation rates of approximately 7 min/inch (4gallons/hr.) and at 5 min/inch showed inadequate filtration of percolating waters to occur in or along the bedrock fractures (Table 3). Downward percolation velocities, i. e., the time required for the tracer water to flow from the bottom of the injection hole and subsequently emerge from the face of the road-cut, ranged from 60-20 ft./hr. at percolation rates of approximately 7 min/inch. At faster "perc" rates (less than 5 min/inch) the percolation velocities were less variable (50-40 ft./hr.). This large variability in percolation velocities was thought to be due, in part, to testing done soon after rainfall and the difficulty in maintaining desired siphoning rates. At these rather

high percolation velocities, it appears that septic-tank effluent which had entered underlying bedrock fractures could contaminate shallow ground water supplies in a very brief time.

At Parvin Lake, tracer waters (inoculated with B. stearothermophilis) added to shallow holes adjacent (2 and 4 ft.) to monitoring wells #1 and #2 were found to be present in the well-waters less than 2 hr. after inoculation of the holes (Figure 4). Thus, heavily contaminated percolating waters, such as septic-tank effluent could travel a considerable distance through coarse soils and bedrock fractures and still contain appreciable levels of microorganisms. Data obtained at both test sites, while not indicative of all mountain building sites, definitely cast some doubt upon the use of minimum percolation rates for site approval of conventional waste disposal systems.

While it was not economically feasible to develop operating waste disposal systems at mountain sites which had the necessary geologic controls, field procedure used in this investigation were developed to simulate the hydrological and microbiological conditions which occur in waste disposal units constructed in mountainous terrains. The two test sites (Poudre Canyon, Parvin Lake) were selected because their geologic characteristics (fracturing, petrography, dip, degree of weathering, extent of soil development) are typical of many Front Range building sites. Injection holes at both

field locations were dug to depths used in leachfield installations and in determining percolation rates. Inoculation of bacteria-laden waters into wells and injection holes was at volumes typically produced by septic tanks at year-around residences.

Whenever procedures are developed to simulate conditions which occur in the environment, inadequacies of these techniques must be evaluated. Problems encountered throughout this investigation included: 1) the difficulty in locating more than two sites on public land in which the geologic controls were representative of mountain building sites and the terrain accessible, 2) time and equipment required to drill water-wells or develop injection holes, 3) transportation and storage of sufficient inocula for the microbiological tests, and 4) the inability to continue inoculation of wells and holes for extended periods of time (weeks) and during the winter months.

Ideally, the inoculum used in the injection tests should have been septic-tank effluent. In this investigation, because of the large gallonages required, river water was amended with municipal waste effluent to produce the inoculum (Table 3). While the bacterial numbers in the amended river water were lower than those found in septic-tank effluent, microbiological tests on the diluted sewage confirmed that bacteria can be transported through bedrock fractures by percolating water. The high percentage of water-wells in the Red Feather Lakes area contaminated with fecal-associated bacteria and

the results obtained at the Parvin Lake site show that microorganisms, once present in the zone of saturation, can be readily transported by the ground water gradient.

In addition to the physical controls imparted upon percolating effluent by fractured and jointed bedrock, the geochemical effects of common rock types on bacterial survival were briefly examined. The purpose of this portion of this study was to determine whether certain rock categories, i. e., igneous, metamorphic, volcanic, etc., could produce rapid bacterial die-offs and thus aid in effluent purification where soils alone were inadequate.

In an attempt to explain the variable geochemical effects on bacterial survival, a regressional analysis was conducted. Analysis of the data on the varying chemical elements of the rock samples (Table 7) and bacterial survival times in the presence of the samples revealed only calcium, sodium and silica were significant in correlation with rapid die-off rates. Trace elements were not included in the analysis since trace analyses were only available for 10 of the rock samples. The pH values of the rock-water aggregates which ranged from 5.7 to 8.4 were not significant from the regressional analysis. The reduced toxic effect during the second exposure may have been due to the solubilization of the calcium and sodium from the fresh rock surfaces during the first exposure and the removal of these solubilized elements prior to the second exposure. While the

results of the geochemical effects on bacterial survival are inconclusive, it appears from the preliminary data that mineralogy of the geologic stratum on percolating effluent to be less important than the physical controls.

Additional laboratory studies on the effect of various clay types (montmorillonite, illite, kaolinite) upon bacterial survival revealed that while clay minerals present in soils are important in the physical absorption of microorganisms (15, 24), their toxic effect on fecal-type bacterial is negligible (Table 11). After two weeks exposure to the three different clay types, coliform levels declined less than one $\log_{10}$ unit from initial inoculation levels. Also, the clay content of the "fines" analyzed did not correlate with bacterial die-off rates.

To date, little work has been done in examining the fate of septic-tank effluent in mountainous terrains which are generally lacking in adequate soil profiles and underlain by fractured crystalline bedrock. The guidelines or regulations, which are presently being employed in evaluating the suitability of mountain building sites for the installation of conventional waste disposal systems, were developed in and for rural non-mountainous areas where municipal waste treatment facilities were unavailable. In these areas, minimum horizontal distances between water-wells and disposal sites as well as the deep soil profiles appeared to be sufficient in most cases. In addition, percolation tests gave a reasonable estimate of soil absorbancy since the underlying soil was fairly homogeneous.

With the accelerated growth and development of the Front Range, there has been an increasing number of mountain homes and cabins being constructed which require both a domestic water supply and waste disposal system. Since dependable and factual guidelines for the safe installation of conventional waste disposal systems at mountain building sites were not available, health agencies have adopted or modified many of the criteria used in evaluating proposed waste disposal sites in non-mountainous areas. Without sufficient field data on the movement of septic-tank effluent in hard rock terrains, the minimum horizontal displacement distance was doubled by public health agencies (100 ft.) hoping that this would prevent contamination of adjacent water-wells; maximum percolation rates (less than 5 minutes/inch) were also established to protect ground water from contamination. This investigation was attempted to generate pertinent data on this problem as well as evaluate regulations presently being employed or undergoing revisions.

Hydrogeological and microbiological results obtained at both the Parvin Lake and Poudre Canyon sites strongly indicate that septic-tank effluent can readily percolate through fractured bedrock and subsequently enter shallow ground water supplies without proper purification. This inadequate purification is due to the lack of clay soils underlying soil-absorption fields or along rock fractures and the high flow velocities of percolating effluent through bedrock fractures.

In addition, bacteria-laden waters entering the zone of saturation are transported in the direction of the local ground water gradient. Such contamination may eventually enter well-waters and surface water supplies posing a health threat to those who subsequently consume this water.

Finally, present criteria being used to determine the suitability and design of conventional waste disposal systems in non-mountainous areas are totally inadequate in evaluating potential waste disposal sites in mountainous terrains. Percolation rates, minimum displacement distances and depth of soils, typically used as parameters for site approval of septic-tank soil-absorption systems in agricultural and urban areas, cannot entirely be used for the evaluation of mountain waste disposal sites. Results of this investigation clearly show that present regulations employed in site approval cannot be considered adequate to protect potable ground water supplies. It is therefore essential that hydrogeologic data such as bedrock fracture patterns, depth and movement of ground waters, seasonal fluctuations in water levels, depth of bedrock weathering, be fully ascertained.

SUMMARY AND CONCLUSIONS

This investigation has shown that fractured bedrock, commonly found underlying domestic leachfields in mountainous terrains, can easily be an avenue for effluent percolation and subsequent contamination of potable ground water supplies. Further, the anisotropic nature of many geologic materials largely controls the direction and rate of movement of contaminated ground waters. From laboratory and field studies, it has been demonstrated that insufficient effluent purification occurs in or along bedrock fractures. Microbial die-off rates as a result of toxicity due to the mineralogy of some common rock types were found to be negligible.

The approval of sites for installation of conventional waste disposal systems has been most often based on percolation rates and horizontal distances between disposal units and water supplies. Hydrologic results obtained at both test sites indicated that percolation rates are not a dependable or factual criterion for site approval in mountain areas. Depending upon the proximity to underlying bedrock fractures, percolation rates can vary considerably within the area of the proposed leachfield site. Thus, site approval based on a single, or even several percolation tests may result in the installation of septic-tank soil-absorption systems where proper effluent filtration can never be adequate.

From the data obtained at the Parvin Lake site, it is obvious that present guidelines which recommend a minimum distance of 100 ft. between water-wells and domestic waste disposal sites are inadequate to protect ground water supplies from contamination in mountain areas.

Continued contamination of shallow ground water supplies by domestic waste waters can result in a gradual deterioration of regional ground water quality. Although microbial die-off and oxidation of organic matter in shallow aquifers does occur, the lack of dissolved oxygen, low temperatures, and the slow rate of dispersion and dilution greatly prolong the time required to remove ground water pollutants.

On the basis of results obtained from this investigation, it can be concluded:

1. Bedrock fractures can readily accept and convey contaminated percolating waters to shallow ground water supplies.
2. The direction and rate of movement of bacteria-laden effluent is largely affected by the anisotropy of the bedrock.
3. The distances traversed by percolating effluent through fractured bedrock was observed to exceed 100 ft. (horizontal). And, it is suspected that distances may exceed several hundred feet.
4. Insufficient microbial filtration of leachfield effluent occurs in or along bedrock fractures and joints.

5. Microbial die-offs due to the mineralogy (geochemistry) of the confining rock stratum is negligible.
6. Moderate percolation rates and large distances between water-wells and conventional waste disposal units cannot insure the continued potability of ground waters in mountainous areas.
7. Fecal-type bacteria present in ground waters may survive several months.

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APPENDIX

TABLE 6A. ROCK SAMPLES; GEOLOGIC DESCRIPTION AND LOCATION

Sample No.	Geologic Description	Location
A1	Trachybasalt(Adel Mtn. Volcano)	Wolf Creek, Montana
B1	Trachyandesite	Wolf Creek, Montana
C1	Log Cabin Granite	Prairie Divide area, Larimer Co., Colo.
D1	Peridotite (Ming Bar Diatreme)	Wolf Creek, Montana
E1	Porphyritic quartz monzonite	Comanche Peak, Mummy Range, Larimer Co., Colo.
F1	Rhyodacite	Wolf Creek, Montana
G1	Trachyandesite	Wolf Creek, Montana
H1	Kimberlite(Sloan Diatreme)	Larimer Co., Colo.
I1	Trachyandesite	Wolf Creek, Montana
J1	Log Cabin Granite	Prairie Divide area, Larimer Co., Colo.
K1	Cordierite-anthophyllite-almandine-biotite-quartz gneiss	South Rustic Quad., Larimer Co., Colo.
L1	Quartz monzonite	Chambers Lake area, Larimer Co., Colo.
M1	Rhyolite	N. E. Rustic Quad., Larimer Co., Colo.

TABLE 6B. ROCK SAMPLES; GEOLOGIC DESCRIPTION AND LOCATION

Sample No.		
A2	Rhyolite	N. E. Rustic Quad., Larimer Co., Colo.
B2	Porphyritic quartz monzonite	Twin Lakes, Colo.
C2	Log Cabin Granite	Prairie Divide area, Larimer Co., Colo.
D2	Silver Plume Granite	Indian Hills, Colo.
E2	Rhyolite	Boston Peak Quad., Larimer Co., Colo.
F2	Muscovite-biotite-quartz shist	Buckhorn Canyon, Larimer Co., Colo.
G2	Rhyolite	N. E. Rustic Quad., Larimer Co., Colo.
H2	Log Cabin Granite	Pingree Park area, Larimer Co., Colo.
I2	Chlorite schist	Buckhorn Canyon, Larimer Co., Colo.
J2	Peridotite(Ming Bar Diatreme)	Wolf Creek, Montana
K2	Quartzofeldspathic schist	Buckhorn Canyon, Larimer Co., Colo.
L2	Quartz monzonite(Log Cabin)	Poudre Canyon area, Rustic, Colo.
M2	Biotite gneiss	South Rustic Quad., Larimer Co., Colo.
N2	Hornblende granodiorite	Buffalo, Colo.
O2	Porphyritic quartz monzonite (Nelson Batholith)	Sirdar, British Columbia, Canada
P2	Quartz monzonite	West Chambers Lake, Larimer Co., Colo.
Q2	Granite	South Rustic Quad., Larimer Co., Colo.

TABLE 7. CHEMICAL ANALYSIS OF ROCK SAMPLES

Chemical Species (%Wt.)	Sample Number					
	A1	B1	C1*	D1*	E1*	F1
SiO_2	51.2	56.5	70.5	43.1	67.5	62.4
Al_2O_3	15.9	15.5	16.2	8.5	14.6	17.3
FeO	3.8	3.9	1.18	6.2	2.3	1.8
Fe_2O_3	6.5	5.7	1.38	2.4	2.9	3.4
MgO	4.6	1.7	0.45	23.5	1.45	1.3
CaO	8.0	4.9	0.90	8.9	2.9	3.0
Na_2O	3.4	4.3	3.0	1.3	3.0	4.9
K_2O	2.6	2.6	5.35	0.57	4.1	3.6
H_2O^+	1.4	1.3	0.69	2.5	0.32	0.58
H_2O^-	0.78	1.2	0.28	0.85	0.14	0.33
TiO_2	0.83	1.2	0.39	0.52	1.05	0.56
P_2O_5	0.64	0.98	0.08	0.62	0.20	0.26
MnO	0.18	0.15	0.07	0.16	0.06	0.11
CrO_3	—	—	—	—	—	—
CO_2	<.05	<.05	—	0.92	—	<.05
Fe	—	—	—	—	—	—
Cr	—	—	—	0.17	—	—
H_2O	—	—	—	—	—	—

* Trace Analysis in Table 8.

TABLE 7. (Continued)

Chemical Species (%Wt.)	Sample Number					
	G1	H1	I1	J1*	K1*	L1*
SiO_2	51.2	32.24	54.3	70.5	57.0	71.9
Al_2O_3	15.0	3.05	19.1	15.3	15.6	15.1
FeO	4.3	1.09	2.6	1.28	13.2	1.36
Fe_2O_3	5.6	7.41	4.3	1.82	2.50	0.91
MgO	5.0	27.13	2.1	0.62	7.4	0.46
CaO	7.2	8.63	5.0	0.95	0.40	1.30
Na_2O	3.4	0.06	4.6	2.95	0.50	2.85
K_2O	3.7	0.84	2.8	6.4	0.25	4.80
H_2O^+	2.6	9.74	1.9	0.92	1.60	0.31
H_2O^-	0.44	2.65	1.6	0.47	0.40	0.12
TiO_2	0.96	1.08	0.56	0.38	1.48	0.30
P_2O_5	0.50	0.54	0.77	0.11	<0.01	0.15
MnO	0.17	0.15	0.11	0.52	0.11	0.03
CrO_3	—	0.16	—	—	—	—
CO_2	<.05	5.2	<.05	—	—	—
Fe	—	—	—	—	—	—
Cr	—	—	—	—	—	—
H_2O	—	—	—	—	—	—

* Trace Analysis in Table 8.

TABLE 7. (Continued)

Chemical Species (%Wt.)	Sample Number					
	M1*	A2*	B2	C2	D2	E2
SiO_2	72.4	74.5	67.8	70.5	70.3	75.0
Al_2O_3	15.7	14.9	16.5	15.5	15.9	13.8
FeO	1.29	—	0.97	1.20	0.39	0.17
Fe_2O_3	2.75	—	0.69	1.61	0.64	0.65
MgO	0.30	0.25	0.59	0.53	1.41	0.20
CaO	0.67	0.20	1.57	0.93	1.75	0.20
Na_2O	4.6	2.6	2.43	2.98	2.41	3.15
K_2O	2.6	4.2	9.12	5.83	7.09	3.85
H_2O^+	—	—	—	0.81	—	1.20
H_2O^-	0.64	0.60	0.01	0.37	0.18	0.40
TiO_2	0.11	0.07	0.28	0.38	—	0.10
P_2O_5	0.07	—	—	0.09	—	—
MnO	0.05	0.03	—	0.06	—	0.02
CrO_3	—	—	—	—	—	—
CO_2	—	—	—	—	—	—
Fe	1.0	0.72	—	—	—	—
Cr	—	—	—	—	—	—
H_2O	—	—	0.09	—	—	—

* Trace Analysis in Table 8.

TABLE 7. (Continued)

Chemical Species (%Wt.)	Sample Number					
	F2	G2*	H2	I2	J2	K2
SiO_2	62.2	73.3	74.6	24.1	42.8	82.1
Al_2O_3	19.2	14.2	0.14	19.5	10.2	8.78
FeO	1.19	—	0.18	1.55	5.4	0.43
Fe_2O_3	2.15	—	0.14	3.45	2.9	0.59
MgO	5.63	0.15	0.64	37.23	19.1	2.93
CaO	2.56	0.75	0.78	—	10.5	1.21
Na_2O	0.48	4.5	2.55	—	1.6	2.71
K_2O	4.34	4.1	6.53	0.95	0.71	0.94
H_2O^+	—	—	—	—	3.3	0.2
H_2O^-	—	—	—	—	0.92	—
TiO_2	—	0.10	—	—	0.63	—
P_2O_5	—	0.09	—	—	0.79	—
MnO	—	0.04	—	—	0.18	—
CrO_3	—	—	—	—	—	—
CO_2	—	—	—	—	0.96	—
Fe	—	1.57	—	—	—	—
Cr	—	—	—	—	--	—
H_2O	1.6	—	—	11.45	—	—

* Trace Analysis in Table 8.

TABLE 7. (Continued)

Chemical Species (%Wt.)	Sample Number					
	L2	M2	N2	O2	P2	Q2*
SiO_2	75.4	65.9	67.2	69.3	73.7	72.0
Al_2O_3	12.91	14.1	15.53	15.23	14.0	14.7
FeO	0.65	4.75	3.3	1.83	1.06	1.28
Fe_2O_3	tr.[1]	2.23	1.7	0.80	0.35	0.36
MgO	0.45	1.05	0.89	1.23	0.75	0.45
CaO	0.48	2.10	2.71	2.85	1.92	0.84
Na_2O	1.72	2.21	3.08	2.75	2.55	3.44
K_2O	8.31	4.60	4.91	5.38	5.70	6.05
H_2O^+	—	1.39	0.23	—	—	0.92
H_2O^-	—	0.10	0.04	—	—	0.12
TiO_2	—	0.80	0.90	0.33	—	0.24
P_2O_5	—	—	0.50	—	—	—
MnO	—	0.07	—	—	—	0.02
CrO_3	—	—	—	—	—	—
CO_2	—	—	0.13	—	—	—
Fe	—	—	—	—	—	—
Cr	—	—	—	—	—	—
H_2O	0.17	—	—	0.28	0.18	—

[1] Trace.

* Trace Analysis in Table 8.

TABLE 8. TRACE CHEMICAL ANALYSIS OF ROCK SAMPLES

Element (ppm)	Sample Number C1	D1	E1	J1	K1	L1
B	15	—	17	15	15	<3
Ba	570	1500	1050	710	25	1200
Be	3.5	—	2.2	3.0	1.5	2
Co	<5	100	10	5	7	18
Cr	<10	1500	53	<10	<10	25
Cu	8	70	40	16	26	—
La	125	70	150	130	55	30
Ni	<5	1000	5	<5	<5	<3
Sc	7	20	8	7.5	48	<3
Sr	90	1000	190	150	40	140
V	19	100	75	24	240	20
Y	120	10	45	52	48	10
Zr	390	70	710	630	220	220
Ga	17	—	22	16	18	17
Pb	60	—	30	30	15	50
Sn	18	—	23	2	12	—
Zn	90	—	110	70	70	85
Rb	—	—	210	330	15	180
Li	—	—	50	40	70	—
Tl	<.2	—	—	—	<.2	—
Ag	<.3	—	—	—	<.3	—

TABLE 8. (Continued)

Element (ppm)	Sample Number M1	A2	G2	Q2
B	<3	<3	<3	<10
Ba	810	410	620	620
Be	3.0	1.5	2.0	0.8
Co	<3	<3	<3	<5
Cr	<5	<5	<5	20
Cu	6	<5	<5	15
La	<10	<10	<10	40
Ni	<5	<5	<5	<5
Sc	<3	<3	<3	<6
Sr	260	60	380	90
V	13	5	15	15
Y	8	10	12	37
Zr	105	25	85	90
Ga	18	17	15	12
Pb	24	15	28	35
Sn	—	—	—	—
Zn	52	72	35	60
Rb	64	128	94	190
Li	—	—	—	60
Tl	—	—	—	—
Ag	—	—	—	—

TABLE 9A. COLIFORMS/ML FROM ROCK-WATER AGGREGATE SAMPLES (FIRST EXPOSURE)

Sample Number	Days after Inoculation 1	2	3	4	5	6
A1	96×10^4	10×10^5	12×10^5	83×10^4	86×10^4	56×10^4
B1	12×10^5	10×10^5	14×10^5	80×10^4	84×10^4	38×10^4
C1	13×10^5	88×10^4	13×10^5	91×10^4	78×10^4	67×10^4
D1	66×10^4	30×10^4	13×10^4	14×10^4	70×10^3	39×10^3
E1	10×10^4	95×10^2	10×10^1	20×10^1	30	1
F1	10×10^5	11×10^5	11×10^5	12×10^5	95×10^4	23×10^4
G1	92×10^4	99×10^4	11×10^5	97×10^4	86×10^4	14×10^4
H1	36×10^4	34×10^4	85×10^3	94×10^3	26×10^4	28×10^3
I1	36×10^4	49×10^4	77×10^4	79×10^4	87×10^4	56×10^4
J1	12×10^5	11×10^5	10×10^5	89×10^4	83×10^4	54×10^4
K1	11×10^5	12×10^5	13×10^5	11×10^5	10×10^5	27×10^4
L1	22×10^5	10×10^2	10	5	0	0
M1	78×10^4	94×10^3	13×10^4	10×10^4	38×10^3	20×10^3
Qtz[1]	46×10^4	25×10^4	70×10^1	11	5	0

[1] Quartz control

TABLE 9A. (Continued)

Sample Number	Days after Inoculation 7	8	10	12	13	14
A1	$75x10^4$	$86x10^4$	$67x10^4$	$52x10^4$	—	$40x10^4$
B1	$61x10^4$	$81x10^4$	$96x10^4$	$61x10^4$	—	$40x10^4$
C1	$93x10^4$	$87x10^4$	$10x10^4$	$92x10^4$	—	$60x10^4$
D1	$73x10^3$	$34x10^3$	$20x10^3$	$62x10^2$	—	$30x10^2$
E1	0	0	0	—	—	0
F1	$78x10^4$	$92x10^4$	$90x10^4$	$93x10^4$	—	$78x10^4$
G1	$71x10^4$	$81x10^4$	$50x10^4$	$30x10^4$	—	$20x10^4$
H1	$70x10^2$	$80x10^1$	$14x10^2$	$64x10^2$	—	$62x10^2$
I1	$81x10^4$	$78x10^4$	$11x10^5$	$82x10^4$	—	$50x10^4$
J1	$99x10^4$	$99x10^4$	$94x10^4$	$96x10^4$	—	$69x10^4$
K1	$82x10^4$	$10x10^5$	$80x10^4$	$10x10^5$	—	$60x10^4$
L1	0	0	—	—	—	0
M1	$55x10^2$	$13x10^3$	$37x10^2$	—	$21x10^2$	60
Qtz	1	0	—	—	—	0

TABLE 9A. (Continued)

Sample Number	Days after Inoculation 16	18	21
A1	43×10^4	75×10^4	29×10^4
B1	44×10^4	70×10^4	37×10^4
C1	47×10^4	86×10^4	55×10^4
D1	22×10^2	47×10^2	44×10^2
E1	—	—	—
F1	60×10^4	68×10^4	—
G1	76×10^3	64×10^3	12×10^3
H1	21×10^2	61×10^1	15×10^1
I 1	75×10^4	64×10^4	—
J 1	71×10^4	51×10^4	—
K1	70×10^4	93×10^4	—
L1	—	—	—
M1	—	60	0
Qtz	—	—	—

TABLE 9B COLIFORMS/ML FROM ROCK-WATER AGGREGATE SAMPLES (FIRST EXPOSURE)

Sample Number	Days after Inoculation 1	2	3	4	5	6
A2	37×10^{4}	55×10^{4}	75×10^{4}	69×10^{4}	50×10^{4}	65×10^{4}
B2	33×10^{4}	32×10^{4}	43×10^{4}	23×10^{4}	25×10^{3}	25×10^{3}
C2	90×10^{3}	10×10^{4}	14×10^{4}	10×10^{4}	12×10^{4}	11×10^{4}
D2	—	38×10^{1}	23×10^{1}	1	0	0
E2	15×10^{4}	15×10^{3}	20×10^{1}	33×10^{1}	8	0
F2	35×10^{4}	39×10^{4}	42×10^{4}	52×10^{4}	60×10^{4}	62×10^{4}
G2	36×10^{5}	11×10^{6}	85×10^{5}	57×10^{5}	38×10^{5}	31×10^{5}
H2	—	18×10^{1}	70	46	61	47
I2	34×10^{4}	40×10^{4}	18×10^{4}	11×10^{4}	55×10^{3}	33×10^{3}
J2	—	0	0	—	—	—
K2	10×10^{3}	36×10^{1}	40×10^{1}	31×10^{1}	22×10^{1}	11×10^{1}
L2	10×10^{5}	14×10^{5}	18×10^{5}	22×10^{5}	27×10^{5}	35×10^{5}
M2	—	38×10^{2}	23×10^{2}	18×10^{2}	31×10^{2}	20×10^{2}
N2	15×10^{4}	63×10^{3}	79×10^{3}	77×10^{3}	63×10^{3}	70×10^{3}
O2	—	10	0	0	—	—
P2	50×10^{3}	54×10^{2}	25×10^{2}	17×10^{2}	15×10^{2}	90×10^{1}
Q2	18×10^{4}	12×10^{4}	14×10^{4}	70×10^{3}	44×10^{3}	29×10^{3}
Qtz[1]	—	18	0	0	—	—
Blk[2]	42×10^{4}	48×10^{4}	45×10^{4}	52×10^{4}	51×10^{4}	49×10^{4}

[1] Quartz control

[2] Blank (100 ml of distilled water plus inoculum)

TABLE 9B. (Continued)

Sample Number	Days after Inoculation 7	8	9	10	12	14
A2	46×10^4	40×10^4	40×10^4	38×10^4	40×10^4	45×10^4
B2	24×10^4	19×10^4	25×10^4	24×10^4	21×10^4	18×10^4
C2	84×10^3	83×10^3	91×10^3	81×10^4	10×10^5	—
D2	—	—	—	—	—	—
E2	—	—	—	—	—	—
F2	59×10^4	54×10^4	55×10^4	49×10^4	46×10^4	39×10^4
G2	18×10^5	22×10^5	13×10^5	79×10^4	93×10^4	65×10^4
H2	46	18	37	27	40	36
I2	26×10^3	—	27×10^3	21×10^3	26×10^3	22×10^3
J2	—	—	—	—	—	—
K2	79	35	33	27	24	21
L2	22×10^5	24×10^5	17×10^5	13×10^5	20×10^5	18×10^5
M2	21×10^2	77×10^1	67×10^1	62×10^1	42×10^1	—
N2	62×10^2	50×10^3	49×10^3	—	42×10^2	—
O2	—	—	—	—	—	—
P2	15×10^1	67×10^1	89×10^1	59×10^1	58×10^1	88×10^1
Q2	24×10^3	14×10^3	14×10^3	11×10^2	52×10^2	36×10^2
Qtz	—	—	—	—	—	—
Blk	38×10^3	—	24×10^4	26×10^4	21×10^4	23×10^4

TABLE 9B. (Continued)

Sample Number	Days after Inoculation 16	18	20	23	25	29
A2	47×10^4	34×10^4	46×10^4	27×10^4	38×10^4	37×10^4
B2	19×10^4	14×10^4	15×10^4	10×10^4	98×10^3	40×10^3
C2	71×10^4	66×10^3	80×10^3	62×10^3	31×10^3	26×10^3
D2	—	—	—	—	—	—
E2	—	—	—	—	—	—
F2	51×10^4	40×10^4	46×10^4	45×10^4	35×10^4	28×10^4
G2	47×10^4	50×10^4	45×10^4	56×10^4	65×10^4	44×10^4
H2	18	0	0	—	—	—
I2	24×10^3	14×10^3	13×10^3	68×10^2	61×10^2	52×10^2
J2	—	—	—	—	—	—
K2	8	14	9	0	0	—
L2	17×10^5	13×10^5	21×10^5	13×10^5	17×10^5	11×10^5
M2	—	53×10^2	89×10^2	78×10^2	71×10^2	13×10^1
N2	28×10^2	30×10^3	29×10^3	18×10^3	66×10^2	17×10^2
O2	—	—	—	—	—	—
P2	46×10^1	29×10^1	66×10^1	46×10^1	32×10^1	5
Q2	17×10^2	25×10^2	32×10^2	14×10^2	42×10^1	10
Qtz	—	—	—	—	—	—
Blk	15×10^4	84×10^3	57×10^3	14×10^3	17×10^2	60

TABLE 10A. COLIFORMS/ML FROM ROCK-WATER AGGREGATE SAMPLES (SECOND EXPOSURE)

Sample Number	Days after Inoculation 1	2	3	4	5	6
A1	$10x10^5$	$79x10^4$	$72x10^4$	$51x10^4$	$46x10^4$	$83x10^4$
B1	$10x10^5$	$62x10^4$	$77x10^4$	$63x10^4$	$48x10^4$	$46x10^4$
C1	$25x10^6$	$83x10^4$	$77x10^4$	$62x10^4$	$48x10^4$	$76x10^4$
D1	$10x10^5$	$45x10^4$	$49x10^4$	$38x10^4$	$56x10^4$	$55x10^4$
E1	$11x10^5$	$61x10^4$	$63x10^4$	$62x10^4$	$32x10^4$	$55x10^4$
F1	$89x10^4$	$94x10^4$	$62x10^4$	$78x10^4$	$92x10^4$	$88x10^4$
G1	$98x10^4$	$64x10^4$	$57x10^4$	$97x10^4$	$67x10^4$	$65x10^4$
H1	$87x10^4$	$49x10^4$	$46x10^4$	$51x10^4$	$51x10^4$	$48x10^4$
I1	$86x10^4$	$76x10^4$	$62x10^4$	$71x10^4$	$90x10^4$	$63x10^4$
J1	$74x10^4$	$81x10^4$	$55x10^4$	$74x10^4$	$86x10^4$	$54x10^4$
K1	$11x10^5$	$41x10^4$	$40x10^4$	$42x10^4$	$65x10^4$	$46x10^4$
L1	$96x10^4$	$51x10^4$	$67x10^4$	$58x10^4$	$72x10^4$	$58x10^4$
M1	$87x10^4$	$53x10^4$	$56x10^4$	$65x10^4$	$73x10^4$	$36x10^4$
Blk[1]	$73x10^4$	$39x10^4$	$19x10^4$	$26x10^4$	$15x10^3$	$40x10^1$

[1] Blank (100 ml of distilled water plus inoculum)

TABLE 10A. (Continued)

Sample Number	Days after Inoculation 7	8	10	12	16	18
A1	64×10^4	93×10^4	82×10^4	68×10^4	—	56×10^4
B1	11×10^4	11×10^3	40×10^3	41×10^2	—	40
C1	55×10^4	11×10^5	49×10^4	61×10^4	—	40×10^3
D1	49×10^4	57×10^4	30×10^4	25×10^4	—	16×10^4
E1	49×10^4	54×10^4	34×10^4	85×10^4	—	—
F1	73×10^4	87×10^4	35×10^4	74×10^4	—	63×10^4
G1	76×10^4	67×10^4	43×10^4	56×10^4	—	11×10^4
H1	35×10^4	32×10^4	44×10^4	33×10^4	—	—
I 1	59×10^4	80×10^4	48×10^4	66×10^4	—	16×10^4
J1	10×10^3	66×10^2	36×10^2	16×10^2	—	—
K1	50×10^4	21×10^4	48×10^4	37×10^4	—	77×10^3
L1	24×10^4	13×10^3	48×10^2	27×10^2	—	14×10^2
M1	70×10^3	43×10^3	29×10^3	30×10^3	—	13×10^3
Blk	9	6	0	0	—	—

TABLE 10A. (Continued)

Sample Number	Days after Inoculation 20	22	28	30	38
A1	36×10^{3}	—	51×10^{4}	64×10^{4}	39×10^{4}
B1	18×10^{1}	36×10^{2}	18×10^{2}	13×10^{2}	89×10^{1}
C1	12×10^{2}	—	—	80×10^{3}	50×10^{3}
D1	29×10^{4}	29×10^{4}	27×10^{4}	75×10^{3}	11×10^{4}
E1	—	—	24×10^{4}	22×10^{4}	11×10^{4}
F1	58×10^{4}	67×10^{4}	59×10^{4}	62×10^{4}	70×10^{4}
G1	15×10^{2}	—	—	34×10^{4}	12×10^{4}
H1	—	30×10^{2}	11×10^{2}	30×10^{1}	81
I 1	—	89×10^{4}	63×10^{4}	56×10^{4}	76×10^{4}
J1	55×10^{1}	59×10^{1}	41×10^{1}	21×10^{1}	18×10^{1}
K1	—	36×10^{4}	38×10^{4}	41×10^{4}	25×10^{4}
L1	16×10^{2}	47×10^{2}	28×10^{2}	19×10^{2}	77×10^{1}
M1	—	—	—	—	30×10^{2}
Blk	—	—	—	—	—

TABLE 10B. COLIFORMS/ML FROM ROCK-WATER AGGREGATE SAMPLES (SECOND EXPOSURE)

Sample Number	Days after Inoculation 1	2	3	4	5	6
A2	10×10^5	88×10^4	79×10^4	67×10^4	56×10^4	85×10^4
B2	86×10^4	76×10^4	96×10^4	56×10^4	55×10^4	74×10^4
C2	10×10^5	11×10^5	65×10^4	85×10^4	42×10^4	56×10^4
D2	88×10^4	67×10^4	62×10^4	78×10^4	33×10^4	76×10^4
E2	74×10^4	82×10^4	82×10^4	68×10^4	46×10^4	69×10^4
F2	98×10^4	76×10^4	61×10^4	71×10^4	54×10^4	61×10^4
G2	73×10^4	31×10^4	23×10^4	93×10^3	20×10^3	49×10^3
H2	76×10^4	90×10^4	70×10^4	73×10^4	44×10^4	73×10^4
I2	91×10^4	69×10^4	79×10^4	12×10^5	51×10^4	71×10^4
J2	89×10^4	10×10^5	65×10^4	57×10^4	22×10^4	46×10^4
K2	85×10^4	82×10^4	72×10^4	60×10^4	29×10^4	83×10^4
L2	11×10^5	11×10^5	83×10^4	71×10^4	27×10^4	49×10^4
M2	10×10^5	16×10^5	91×10^4	76×10^4	42×10^4	83×10^4
N2	80×10^4	73×10^4	73×10^4	68×10^4	50×10^4	71×10^4
O2	78×10^4	83×10^4	80×10^4	65×10^4	38×10^4	85×10^4
P2	74×10^4	54×10^4	80×10^4	55×10^4	18×10^4	31×10^4
Q2	82×10^4	92×10^4	87×10^4	44×10^4	93×10^4	90×10^4
Blk[1]	73×10^4	39×10^4	19×10^4	26×10^4	15×10^3	40×10^1

[1] Blank (100 ml of distilled water plus inoculum)

TABLE 10B. (Continued)

Sample Number	Days after Inoculation 7	8	10	12	16	18
A2	62×10^4	99×10^4	77×10^4	69×10^4	55×10^4	—
B2	73×10^4	91×10^4	65×10^4	52×10^4	58×10^4	—
C2	89×10^4	87×10^4	55×10^4	64×10^4	33×10^4	61×10^4
D2	79×10^4	86×10^4	66×10^4	46×10^4	64×10^4	24×10^4
E2	54×10^4	77×10^4	66×10^4	34×10^4	—	—
F2	30×10^3	92×10^4	48×10^4	—	—	—
G2	16×10^2	63×10^2	—	19	1	0
H2	63×10^4	65×10^4	67×10^4	48×10^4	—	—
I2	74×10^4	36×10^4	16×10^3	26×10^4	—	—
J2	47×10^4	46×10^4	18×10^4	29×10^4	—	20×10^2
K2	91×10^4	83×10^4	68×10^4	52×10^4	—	33×10^4
L2	30×10^3	53×10^2	44×10^2	43×10^2	—	—
M2	65×10^4	57×10^4	14×10^4	27×10^3	—	12×10^3
N2	86×10^4	66×10^4	60×10^4	49×10^4	—	70×10^3
O2	69×10^4	12×10^4	60×10^2	60×10^2	—	20
P2	21×10^3	68×10^2	48×10^2	28×10^2	—	—
Q2	97×10^4	31×10^4	80×10^2	67×10^4	—	20×10^3
Blk	9	6	0	0	—	—

TABLE 10B. (Continued)

Sample Number	Days after Inoculation 20	22	28	30	38
A2	21×10^4	79×10^4	78×10^4	56×10^4	56×10^4
B2	75×10^3	48×10^4	34×10^4	28×10^4	12×10^4
C2	51×10^4	73×10^4	51×10^4	53×10^4	50×10^4
D2	54×10^4	56×10^4	45×10^4	38×10^4	14×10^4
E2	—	19×10^4	83×10^3	17×10^3	15×10^1
F2	—	12×10^4	—	—	12×10^2
G2	—	—	—	—	0
H2	19×10^4	10×10^3	36×10^4	20×10^4	21×10^4
I2	—	82×10^2	65×10^2	26×10^2	75×10^1
J2	—	14×10^4	71×10^3	27×10^3	12×10^2
K2	56×10^4	74×10^4	69×10^4	46×10^4	32×10^4
L2	—	29×10^2	18×10^2	13×10^2	78×10^1
M2	14×10^2	14×10^3	84×10^2	30×10^2	62×10^1
N2	35×10^4	48×10^4	46×10^4	39×10^4	21×10^4
O2	15×10^2	12×10^2	96×10^1	54×10^1	21×10^1
P2	18×10^1	17×10^2	16×10^2	19×10^1	30×10^1
Q2	10×10^2	90×10^1	76×10^1	13×10^1	27×10^1
Blk	—	—	—	—	—

TABLE 11. COLIFORMS / ML FROM CLAY-WATER SAMPLES

Clay Type	Days after Inoculation 1	2	3	4	5	6
Montmorillonite	10×10^4	89×10^4	86×10^4	14×10^5	96×10^4	12×10^5
Illite	27×10^4	24×10^4	25×10^4	11×10^5	12×10^5	12×10^5
Kaolinite	81×10^3	27×10^4	19×10^3	22×10^4	23×10^4	17×10^4
Blank	12×10^5	86×10^4	98×10^4	11×10^5	98×10^4	11×10^5

TABLE 11. (Continued)

Clay Type	Days after Inoculation 7	9	11	14	17
Montmorillonite	12×10^5	97×10^4	56×10^4	—	10×10^4
Illite	11×10^5	12×10^5	13×10^4	13×10^5	95×10^4
Kaolinite	15×10^4	85×10^3	84×10^3	37×10^3	30×10^2
Blank	11×10^5	10×10^5	99×10^4	10×10^5	17×10^3

GLOSSARY OF GEOLOGIC TERMS

ground water - that part of the subsurface water which is in the zone of saturation.

zone of saturation - that zone in which the functional permeable rocks are saturated with water under pressure equal to or greater than atmospheric.

zone of aeration - the zone in which the interstices of the functional permeable rocks are not filled (except temporarily) with water. The water is under less than atmospheric pressure.

fractures - breaks in rocks due to both internal and external stresses.

joint - in geology, a fracture or parting which interrupts abruptly the physical continuity of a rock mass, but along which no lateral movement has occured.

fluvial - of, or pertaining to rivers; produced by river action.

colluvial - talus and cliff debris.

igneous rock - formed by solidification of hot mobile material termed magma.

metamorphic rock - includes all those rocks which have formed in the solid state in response to pronounced changes in temperature, pressure, and chemical environment, which takes place, in general, below the depths of weathering and cementation.

sedimentary rock - rocks formed by the accumulation of sediment in water (aqueous deposits) or from air (eolian deposits).

anisotropy - condition of having different properties in different directions.

percolation - movement, under hydrostatic pressure of water through the interstices of the rock or soil, except movement through large openings such as caves.

amphibolite - a crystalline rack consisting mainly of amphibole and plagioclase. Quartz is absent, or present in small amounts only.

amphibole - a mineral group, general formula $A_{2-3}B_5(Si, Al_4)O_{11}(OH)_2$, where A is aminly Mg, Fe^{++}, Ca and Na; B is mainly Mg, Fe^{++}, Al, and Fe^{+++}.

illite - name used for a group of clay minerals abundant in argillaceous sediments.

granite - a plutonic rock consisting essentially of alkalii felspar and quartz. Sodic plagioclase, usually oligoclase is commonly present in small amounts and muscovite, biotite, and hornblende.

kaolinite - a common clay mineral. Two-layer hydrous aluminum silicate having the general formula $Al_2(Si_2O_5)(OH)$. It consists of sheets of tetrahedrally coordinated silicon joined by an oxygen shared with octahedrally coordinated aluminum.

montmorillonite - a group of clay minerals whose formulas may be derived by substitution in the general formula $Al_2Si_4O_{10}(OH)_2$ with dificiences in charge in the tetrahedral and octahedral positions balanced by the presence of cations, most commonly Ca and Na, subject to ion exchange.

dip - the angle at which a stratum or any planar feature is inclined from the horizontal.

infiltration - the flow of a fluid into a substance through pores or small openings. It connotes flow into a substance in contradisinction to the word percolation, which connotes flow through a porous substance.

neutron logging - radioactivity logging method used in boreholes in which a neutron source provides neutrons which enter rock formations encountered and induce additional gamma radiation which is measured by use of a scintillation crystal. The gamma radiation so induced is related to the hydrogen (moisture) content of the rock.

stream terrace - stream-cut rock terrace with thick cover of slope wash.

strike - perpendicular to the direction of the dip.

exfoliation - the breaking or peeling-off of scales, lamellae, as concentric sheets from bare rock surfaces.

outcrop - the coming out of a stratum to the surface of the ground.

porphyritic - a textural term for those igneous rocks in which larger crystals (phenocrysts) are set in a finer groundmass which may be crystalline or glassy, or both.

aquifer - a formation, group of formations, or part of a formation that yields water in economic quantities.

glacial drift - sediment in transport in glaciers, deposited by glaciers, and predominantly of glacial origin, made in the sea or in bodies of glacial meltwater.

phreatic - pertaining to all water in the zone of saturation.

plagioclase - a mineral group, formula (Na, Ca)Al(Si, Al)Si_2O_8; a solid solution series from $NaAlSi_3O_8$ (albite) to $CaAl_2Si_2O_8$ (anorthite); one of the most common rock-forming minerals.

feldspar - a group of abundant rock-forming minerals; includes microcline, orthoclase, plagioclase, anorthoclase.