Research Technical Completion Report

HYDROGEOLOGIC FRAMEWORK OF THE BOISE AQUIFER SYSTEM ADA COUNTY, IDAHO

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Moscow, Idaho 83843

March, 1992

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Idaho Water Resources Research Institute
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ABSTRACT

The city of Boise relies upon the underlying groundwater resource for 90 percent of its public water-supply. The cold-water aquifers are saturated sedimentary deposits of rivers and lakes that existed 9-to-2 million years ago. The basin-fill sediments which comprise this system of aquifers are divisible into five distinct hydrogeologic settings which differ on the basis of sediment type, geophysical log character, and hydraulic properties. A large buried alluvial-fan/fan-delta complex (**the Boise Fan**) occupies the head of the basin. Erratic and spiky signatures of natural gamma and electrical resistivity logs are typical of these thinly bedded and complexly intercalated sand, gravel, and silty mud deposits. Color is characteristically the yellowish brown of oxidized iron; reflecting the subaerial depositional environment of an alluvial fan. Down-valley gradations in sediment type show a general increase in unit thickness (smoother and more gradual deflections of geophysical log-response), and sediment color more typically gray; reflecting transition to the lake environment of deposition. Basinward, the ancient fan materials grade into lake/fan transitional sediments which grade to predominantly lake sediments which grade to gray mudstones and fine sand layers of the deep lake environment. These translate into hydrogeologic settings respectively named: the **Lake-to-Fan Transition**, **Central Boise Lacustrine Aquifers**, and the **Deep Artesian Lacustrine Sands of West Boise**. A fifth setting are the **Lake Margin Sands** comprised of a wedge-shaped sand "sheet" of fluvial and lake margin sediments which thin away from the mountain front and may be separated from the other hydrogeologic settings by an erosional unconformity located 400-to-600 feet below the present day surface.

Specific capacities of efficient wells open to 80-to-100 feet of sand are highest in the **Lake-to-Fan Transition** and the **Central Boise Lacustrine Aquifers** (25-to-40 gallons per minute per foot (gpm/ft)), lowest for the **Boise Fan** (8-to-15 gpm/ft), and intermediate for the **Deep Artesian Sand Aquifers of West Boise** (15-to-20 gpm/ft) within the **Boise Fan** aquifer. As a result of screen and filter-pack design based upon careful attention to sampling drill cuttings, sieve analysis of sands, and geophysical log location of aquifers, efficiency and productivity of new wells has been greatly increased. For example, recent wells in the **Boise Fan** setting, completed with carefully placed screen and filter-packs, have resulted in production wells near sites where previous wells were considered unsuccessful.

The degree to which the waters of the Boise aquifers are confined generally increases down-valley. Piezometric levels, inferred from static water-levels of wells, in east Boise change very little as wells are deepened and often the static levels decline slightly with depth. In west Boise the static levels in wells rise significantly as wells are deepened, and many are flowing artesian wells with heads up to 10 feet above surface. Sub-surface mapping of aquifer units and overlapping hydraulic well-test data suggest that hydraulic continuity exists across the system. Below east Boise, this hydraulic interconnection is most direct and inter-aquifer leakage is measurable over pumping periods of hours-to-several days. The subsurface of west Boise has the greatest degree of separation between aquifer units and leakage is more difficult to measure.

The system of semi-confined and unconfined cold-water aquifers beneath Boise has boundaries related to lateral changes in the types and occurrence of lake and river sediments, and to crustal faulting. Interbedded sand, silt, and claystone of the upper

Miocene and early Pliocene Idaho Group are the primary water-yielding strata. Production is mostly from the upper 500 feet in east and north-central Boise, and from as deep as 900 feet in south, west, and southeast Boise. The depths to which drinking-water aquifers extend is limited by an underlying sequence of relatively impermeable volcanic rocks identified by seismic exploration and deep-well data. In addition, a boundary to the available "cold" (less than 85 degrees F) water aquifers of the Boise area is defined by state law as the 85-degree isotherm. Water from deep wells may have temperatures in excess of 85 degrees F, and appropriation of this "low-temperature geothermal" groundwater is currently restricted by the Idaho Code.

Increasingly, we are discovering instances of local contamination of the surface-gravel aquifer. The present floodplain of the Boise River and the flight of river-terrace benches south of the river are mantled by a "sheet" of river gravels 30-to-100 feet thick. Groundwater recharge to the deeper aquifers is via these porous and permeable, saturated surface gravels. Increased groundwater withdrawals, commensurate with population growth, have possibly accelerated recharge (and so too, the downward movement of surface pollutants) by increasing vertical hydraulic gradients. Overbored wells with continuous surface-to-depth gravel packs, wells open to multiple aquifers, and improperly abandoned wells with deteriorating casing are also conduits for polluted shallow groundwater to enter the deeper aquifers. It is recommended that filter-packs be separated with bentonite-based seals within the formation/casing annulus and that surface casing be sealed by being driven into a low-permeability unit.

Continued urbanization of flood-irrigated agricultural land and lining/sealing of the larger canals is beginning to cause a decrease in the amount of water available as replenishment to the groundwater reservoirs. Reduction of recharge, coupled with increased pumpage will result in lowered water-levels in wells. Water-levels in wells of the east Boise area are presently in decline and have lowered, on average, over 40-feet during the last 20 years. A possible remedy to declining water-levels in the upper basin is artificial recharge to the **Boise Fan** aquifer.

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INTRODUCTION

Purpose

Groundwater constitutes 90 percent of the public water supply for the city of Boise, Idaho. Boise Water Corporation (BWC), a public utility, depends upon the groundwater resource beneath the Boise River Valley for about 90 percent of its supply. The major part (80% to 90%) of production is from wells 350 to 600 feet deep completed within confined and semi-confined sand aquifers. Current annual production is about 12 to 13 billion gallons (36,900 to 39,900 acre-ft). Peak summer pumpage in late July and early August 1990 and 1991 was 71 million gallons per day. Winter pumpage ranges between 12 to 17 million gallons per day. BWC is experiencing shortages during drought years in certain parts of its distribution system.

At this time, very little published information is available on the geologic framework, continuity, and sustainable yield from this system of aquifers, yet the vitality of the city and future economic development are dependent upon this resource. This report presents the results of a one-year study of the geologic framework of the basin. It will be followed by a report on the hydraulic testing of the Boise aquifer system and another on computer simulation of subsurface hydrogeologic conditions.

The system of confined, semi-confined, and unconfined cold-water aquifers (less than 85 degrees Fahrenheit (85° F)) beneath Boise has boundaries related to lateral changes in the types and occurrence of lake and river sediments, and to crustal faulting. Interbedded sand, silt, and claystone of the upper Miocene and early Pliocene Idaho Group are the primary water yielding strata. Production is mostly from the upper 500 feet in east and north-central Boise, and from as deep as 900 feet in south, west, and southeast Boise.

The depths to which drinking-water quality aquifers extend is limited by an underlying sequence of relatively impermeable volcanic rocks identified by seismic exploration and deep well data. In addition, a boundary to the available "cold" water aquifers of the Boise area is defined by state law as the 85° F isotherm. Water from deep wells may have temperatures in excess of 85° F, and appropriation of this "low temperature geothermal" water is currently restricted by Section 42-233 of the Idaho Code. Coincident with higher temperatures, geothermal groundwater of the Boise area can have fluoride levels up to 18 mg/l which is several times higher than the current EPA drinking-water standard of 4 mg/l.

It is not a difficult task to drill and successfully complete water wells at most locations within the Boise Valley. Historically, the need for additional water supply has required nothing more than the drilling of additional wells. We are now (1992) rapidly approaching a situation where arbitrary siting of new production wells, without consideration of subsurface geology, will cause interference effects within existing wells. This will result in lowering of water levels in wells and inevitably in water rights arbitration. Water rights disputes will be settled in court, with or without detailed knowledge of subsurface geologic conditions, but meaningful evaluation and/or remediation of contaminated groundwater cannot be done without such detailed knowledge.

Recent increases in population, combined with drought conditions which have persisted for several years, have increased water demand and groundwater pumpage. Fifteen new wells have been completed since 1988 by Boise public utilities, of which two are replacements for existing production wells. Excluding replacement wells, new municipal production wells since 1988 represent an additional water production capability of 18.5 million gallons per day. Several new production wells are currently under construction and others are proposed. A surface-water treatment plant is presently under consideration by BWC and is due on line in 1993/94 with capability to treat and supply 8 million gallons per day using water from the Boise River and shallow, unconfined, "surface" aquifers. About half of this capacity represents additional "new" water. At maximum future capacity of 20 million gallons per day the treatment facility will supply only 20 percent of present summer demand.

Replenishment of the cold-water aquifers is most certainly from the Boise River system, its various artificial diversions, and from foothills streams; however, the dynamics and quantities of recharge are not clearly understood. For long-term planning of the regional water resource, for the location and design of future wells, and for protection of the resource from contamination, all water users in the area need a better understanding of the groundwater system. Similar needs are shared by the Idaho Department of Water Resources, and by the Idaho Division of Environmental Quality who regulate the use and protect the quality of the resource, respectively.

Scope

This investigation constitutes the first phase of a three year study of the groundwater system. The first-year study is designed to provide necessary data to design aquifer tests to estimate aquifer coefficients (second phase) and to develop an understanding of the three-dimensional geology of the system necessary as input for a computer model (third phase). Such a model and supporting data will be useful for estimating the sustainable yield from the system, designing future well fields, and evaluating the effects of surface activities that could lead to contamination of the drinking-water aquifers.

Geophysical logs, driller's records, seismic data, and detailed geologic study of thirteen new production and test wells provide a basis for: 1) determining the physical boundaries of Boise area aquifers 2) the construction of detailed stratigraphic and structural cross-sections through the valley (Profiles 1 - 7), 3) characterization of the basin-fill sediments which contain the groundwater resources (Well Logs), 4) calibration of borehole geophysical logs to local geologic conditions (Well Logs), and 5) subdivision of the water bearing section into hydrogeologic units for the purposes of conducting representative aquifer tests.

Location

This study was conducted within an area bounded to the east and to the south by Tenmile ridge, on the north by the foothills of the Boise Front, and on the west by Cloverdale Road. These limits essentially coincide with those of the Boise City Area of Impact (1990). Figure 1 is a location map for the project. In general, the study is concerned with the upper 1000 feet of sedimentary section although data to these depths is not available for some localities.

Acknowledgements

Financial support for this project was provided by the Boise Water Corporation and its parent company General Water Works who granted $30,587 to Boise State

University (BSU) Department of Geosciences to conduct the one year study. Matching funds of $11,200 were awarded by the Idaho Water Resources Research Institute at University of Idaho, Moscow through the U.S. Geological Survey's Section 104 Water Resources Research Program. Contributions from BSU, a proportionate commitment from South County Water Company, and additional monies in the form of geophysical logging fees bring the total support for the one-year study to $66,800.

The authors would like to recognize the following organizations and individuals for their cooperation in this investigation:

Thanks to Wayne Booe, General Water Works - Western Region vice president, for his encouragement and continued support.

Dan Brown and Jon Bowling of the Boise Water Corporation's engineering department along with Jim Mooney and Bob Lawrence of the corporation's production department have been instrumental in coordinating all aspects of the project. Dan Brown's attention to mediating drilling, consulting, research, regulatory, and corporate interests is in large part responsible for the success of this study.

We are indebted to well drillers in the area for all their shared knowledge, for the many interruptions to their work, for taking good samples, and for not laughing too hard when we step in the mud-pit. A special thanks to Wayne E. Stevens and Sons who have been an integral part of this investigation from the beginning. The Stevens' interest and assistance were indispensable in the development of several of our procedures, calibrating geophysical logs to local geology, and during several successful "fishing" trips. John Sullivan, Earl Skinner,

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For allowing us access to wells we would like to thank Keith Stokes (South County Water Company), Paul Wise (Mesa Water Corp.), Gene Wortham (State of Idaho Department of Transportation, District 3), Paul Philbrook (Boise Parks Dept.), Colleen Ramsey (Idaho Power), Bob and Bonnie Price (Capital Water), Robert Griffiths (Boise Warm Springs Water District), and Vic Lewis (Micron Technology - Water Services).

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Especial appreciation to Will Burnham for his encouragement, guidance, and constructive criticism. Will's campaigning for the need of a better understanding of the resource led to initiation of this study.

Previous Investigators

Previous Work on the hydrogeology of the Boise Valley

Earliest discussion of the cold "artesian" water in the Boise area is found in Lindgren (1897) and Russell (1902, 1903) who documented the few wells of the city cold-water supply located in the foothills gulches, and typically about 400 feet deep. Russell (1902) recognized the western Snake River Plain as an artesian basin which he called the "Lewis artesian basin" after an older name of "Lewis River" for the Snake River. The earlier literature referred to the sedimentary section in the Boise Valley as the Payette Formation. Later workers redefine this section as part of the Idaho Group of formations.

Nace and others (1957) attempted to quantify flows and project the effects of development in certain parts of the Boise Valley and they also discussed the history of diversions from the river and their importance as sources of groundwater recharge to the aquifer system. Nace's report (1957) and that of Dion (1972) document the increase in groundwater levels that occurred in the benches south of the river when large scale diversion works and canals were constructed after 1906. Both reports identified the clay, silt, and sand of the Idaho Group as the source of moderately deep artesian water in the Boise Valley. In their studies, the hydrogeologic importance of the 30 to 100 feet of permeable gravels mantling the flood plain and the flight of river terrace steps is also recognized. Nace and others (1957) implied that recharge to the deeper aquifers is via these porous and permeable saturated surface gravels. Their study did not address the complexities of strata in the Idaho Group or fault boundaries of aquifers.

Nace and others (1957) estimated the hydrologic budget for the Boise Valley, as of 1950. They considered the Boise River drainage area between the Boise Diversion Dam

(New York Canal intake) and Notus (five miles west of Caldwell) for the base period 1931-1950. The average annual input of river flow at the Diversion Dam was 1,760,000 acre feet. Their estimate of the average annual precipitation input over this reach of the drainage basin was 708,200 acre feet. About 480,000 acre feet was released at the diversion dam as unusual flows and to serve downstream water rights on the river. The average annual river flow at Notus amounted to 701,000 acre feet - as a result of - release at the diversion dam, surface water return through drainage ditches, and groundwater discharge to the river. No estimate was made of return flow to the river from municipal waste water treatment plants or recharge to the shallow groundwater system from septic tank seepage. Population of the study area in 1950 was 131,000 people, and we estimate that the per capita waste-water production was about 200 gallons per day. About 80,000 people may have been on sewer systems discharging through treatment plants to the river, which suggests an average annual return flow estimate of 17,900 acre feet. About 31,000 may have been on septic systems which suggesting an annual return to shallow ground water of about 6,900 acre feet. Small tributary streams from the foothills to the north, such as Dry Creek and Cottonwood Creek are estimated by Nace and others (1957) to contribute about 10,000 to 15,000 acre-feet annually. They estimated the net annual depletion from all causes to be 590,000 acre-feet, by considering the area under crop irrigation, evapotranspiration from non-irrigated land, and evaporation from reservoirs.

At the time of the study by Nace and others (1957), the annual non-irrigation withdrawal of ground water was estimated at 22,000 acre feet for the Boise River Valley. The annual groundwater withdrawal for irrigation was estimated at 128,000 acre-feet. No attempt was made to draw a distinction between shallow aquifer and deep aquifer withdrawal - nor to estimate return flow from municipal waste treatment plants along the river. No estimate was made of the subsurface underflow of ground water out of the study area.

The hydrologic budget with a greater emphasis on ground water was re-evaluated by Dion (1972) for the years of 1953 and 1970 for an area of the valley extending from the Boise Diversion Dam to Middleton; thereby excluding the 9-mile reach of the river from Middleton to Notus (the Caldwell area) which was included in the study by Nace and others (1957). The following budget is the estimate for 1970 from Dion (1972). Diversions from surface streams was 732,000 acre feet (principally the Boise River at the Diversion Dam). Groundwater pumping from the deep aquifer was 135,000 acre feet, and from the shallow aquifer, 10,700 acre feet. Water consumption (i.e. that not available for recharge) was estimated at 340,000 acre feet, of which 26,900 was water delivered by sewers to the river. From this, Dion (1972) estimated that 500,000 acre feet are recharged to the surface aquifers. Transfer of water from the surface aquifers to the deep aquifers is not estimated, and Dion (1972) shows a deficit (negative recharge) to the deep aquifers equal to the pumpage of 135,000 acre feet, and states (p. 15) that there was no way from data available to determine what proportion of water is transferred from the shallow aquifers to the deep aquifers.

In an effort to understand the discharge of shallow groundwater and drainage ditch water back to the Boise River, Thomas and Dion (1974) conducted an interesting experiment utilizing a situation when flow from Lucky Peak Dam was virtually shut off, on November 18 and 19, 1971 (Figure 2). No significant inflow of water entered the river in the reach from just below Lucky Peak Dam to the Capitol Boulevard crossing, 10 miles downstream of the Dam. Between Capitol Boulevard and Eagle Road, about 90 cubic feet per second (cfs) entered the river. From Eagle Road to Middleton, an additional 150 cfs entered the river. From Middleton to the mouth of the river most of the added inflow of about 760 cfs is from drainage ditches and tributary streams. Flow near the confluence with the Snake River was gauged at 1,010 cfs, of which about 20 per cent was accounted for as inflow from seeps and short surface drains, and about 80 per cent was from surface drainage channels tributary to the river. Nearly 60 per cent of the total inflow entered the stream in the 20-mile reach between Star Road and the gauge at Notus.

Dion (1972) constructed a water-table elevation map (Figure 3) for the Boise River Valley. The map is an interesting guide to understanding recharge patterns in the valley. Significant is the groundwater ridge extending west from Barber Dam. The ridge is a result of seepage from diversion ditches which began about 1912 with the completion of the New York Canal and part of the Boise Reclamation Project. Dion, (1972) found that about 550,000 acre-feet of diverted river water and precipitation on the area is recharge to the shallow aquifer system. He estimated that 135,000 acre-feet was removed from the deep aquifer by pumpage. The extent to which the 135,000 acre-feet was replenished by recharge from the shallow aquifer is not known at this time. Dion's map showed the water-table surface to slope to the south from the crest of the ridge toward the Snake River. Prior to major diversions, it is likely that the Boise River, as it entered the Snake River Plain, was a losing stream along this reach below the present position of Lucky Peak Dam. It will be shown later, in discussions of the hydrogeologic framework, that the bed of the river above Barber Dam is underlain by impermeable strata, whereas the river bed below Barber Dam may have good hydraulic connection to the deeper aquifers via the sheet of floodplain gravel of the present-day Boise River.

A detailed study of the shallow groundwater system of the southwest Boise area, between Orchard and Cloverdale Avenues, is reported by Burnham (1979). He discussed much more thoroughly the water-table contours in that study-area as compared to Dion (1972). Burnham's map of the groundwater divide in the deeper aquifers shows that groundwater flow in 1979 was both southwestward and westward in this area. He stated that no unsaturated zone exists between the shallow and deep aquifers and that hydraulic connection is continuous. In this study Burnham showed the dominance of canal seepage and irrigation application as a source of recharge to the shallow aquifer in the bench area.

At this point in our study (Phase I) we will not update the estimate of the water budget published by Dion (1971). Discussion of the water budget will be included in the third-year report, after hydraulic testing and computer modeling.

An additional aspect of the water budget not addressed in previous reports is return flow to the Boise River of treated municipal waste water. At the present time (1992) the Boise Lander Street Plant discharges about 8.9 to 9 million gallons per day; the West Boise Plant discharges about 10 million gallons per day. Meridian discharges about 1.2 million gallons per day into Five Mile Creek which is tributary to the Boise River. Nampa discharges about 6 to 7 million gallons per day, and Caldwell discharges about 5 million gallons per day. Currently, the total waste-water plant discharge is 31.2 million gallons per day, or 35,000 acre-feet per year, about twice the amount estimated by Nace and others (1957) for 1950.

Previous work on aquifer parameters

Most pump tests in the Boise River Valley have been performance tests of individual wells, for purposes of determining pump size. Hydraulic parameters of aquifers and wells in the Boise area, determined by long-term controlled pump tests with observation wells, have not been published or made public with the exception of Nace and others (1957, p. 54-61), Scanlan (1988) and Feast (1991) which will be discussed later.

Nace and others (1957) report on several well tests west of Boise, but they do not provide details of depth and well construction.

Wood and Anderson (1981) reported on pump tests by Kelly (1976) for wells completed into confined units of fine sand 380 to 600 feet deep near Nampa, Idaho. In a 24-hour test at 1080 gallons per minute (gpm) Kelly estimated a specific capacity of 24 gpm/ft, transmissivities between 200,000 and 160,000 gallons per day per foot (gpd/ft) (26,700 and 21,400 ft^2/day), and a storativity of 6×10^{-4} (dimensionless).

A pumping test on the newly constructed BWC River Run production well was conducted by Scanlan (1988). In testing the 112 foot screened section of medium to coarse sand aquifers (200 to 480 feet deep) for a 10 hour pump period and a 3-day recovery, he determined an apparent transmissivity of 50,000 gpd/ft (6600 ft^2/day) for the early part of the test. However, after 45 minutes, hydraulic barriers were reached by the cone of depression. Specific capacity of the well, after 10 hours of pumping at 1880 gpm was 14.5 gpm/ft. Using the BWC Logger production well (Figure 4) as an observation well, Scanlan (1988) estimated values of apparent transmissivity and apparent storativity for the River Run test at 5000 to 10,000 gpd/ft (660 to 1300 ft^2/day) and 5×10^{-5} respectively.

Wood (1988) reviewed all available pumpage-drawdown data for deep wells (600 to 1200 feet deep) in central and east Boise and found that wells open to 100 or more feet of sand units have specific capacities of 4 to 30 gpm/ft.

Previous computer modeling of the western plain region

Hydrogeology of the entire western Snake River plain has been reviewed from a regional perspective by Newton (1991) and Lindholm (1986). Newton reports on a finite-difference modeling of groundwater flow for the western plain, treating the geologic framework as a 3-layer system. The upper layer of sedimentary rocks is estimated at 500 feet thick, with a transmissivity between 1500 and 21,500 ft^2/day and a storage coefficient of 1 X 10^{-1}. The middle unit of sedimentary rocks is estimated to be 1000 to 4000 feet thick with the collective transmissivities of the fine sand units and mudstones amounting to 900 to 12,000 ft^2/day and storage coefficient of 0.004. The underlying unit of volcanic rock is estimated to have a transmissivity of 8,600 ft^2/day, and a storage coefficient of 0.007. Lindholm (1986) suggested that some water from the deep volcanic section leaks upward into the sedimentary unit, and that vertical hydraulic conductivity for the entire system ranges from 9 to 900 feet/day.

METHODOLOGY

Several of the procedures utilized for this research are modifications of subsurface and well-site geological techniques used by the petroleum industry. These procedures, modified for water wells, are discussed below.

Geophysics and Drilling Operations

BSU's mobile borehole geophysics unit was assembled shortly before the commencement of this investigation and continues to expand its capabilities. Many of the early logs were run using an older Well Reconnaissance Inc. logging system donated to the University by Hunt Minerals Corporation. Well logs from this older unit, generated interest among drillers in the Boise Valley who appreciated help locating sandy zones in "streaky" formations. Also interested were owners of wells who were concerned about water temperatures and compliance with the Idaho Geothermal Resources Act (1972) which places restrictions on use of waters in excess of 85° F. Many useful natural gamma-ray and temperature logs were produced on analog strip charts using this system until 1989. State Board of Education research funds and continued support from Boise Water Corporation allowed for the purchase of a computer based, digital acquisition system using a Mt. Sopris 3000 logger and computer logging software developed by Neil Smith of COLOG, Inc. The new system is "state of the art" and capable of producing filtered and/or processed logs at any scale. Most logs recorded since 1990 are on the newer system. Some of the earlier logs give (uncalibrated) relative values of electrical resistivity but by late 1990, calibration procedures were established and most logs recorded since then are calibrated to a quantitative base-line so that the log trace excursions can be interpreted quantitatively.

Geophysical logs provide a vital record for a water well; they also supplement and greatly improve interpretation of drill cuttings logs. Many professionals believe that geophysical logging of water wells should become a standard practice in Idaho for completion design and also to provide an objective record of lithology and other conditions in wells. As will be demonstrated in this report, the subsurface geology can be interpreted more accurately using these techniques in a new uncased wellbore. We emphasize "uncased" because resistivity logging requires a water or mud-filled hole without casing. Resistivity and other electrical-current based logs, which essentially measure the ability of various rock layers to conduct electrical current, are "short circuited" by steel casing or are insulated from the formation by plastic casing. Natural gamma-ray logs measure the natural radioactivity within formations. Gamma-rays can penetrate casing materials, and thus useful gamma-ray logs can be run in cased wells. Because radioactive levels of most rocks are relatively low, the presence of casing has the effect of attenuating the log response and reducing the sensitivity of the tool to changes in lithology. For this reason natural gamma-ray logs from uncased well-bores are superior to logs run in cased wells. Another advantage to open-hole logging is that caliper logs can be run. The caliper log, which measures the diameter of the borehole, is important if swelling or caving of formations has occurred within the wellbore. Uncemented sands of good aquifers in the Boise Valley can often be detected as washed-out or caved zones. Voids in the borehole wall and/or narrow swollen sections may have an effect on log response. Caliper measurements can be used to correct logs for such effects and to locate caving formations. High quality data require a great deal of coordination between geologist and driller so that good open-hole logs are obtained before the hole is cased.

Interpretation of gamma-ray information obtained from older wells, although helpful, is somewhat limited for the following reasons. The gamma-ray response of the formation is attenuated by large well-bores (more than 24-inches in diameter), and thick, or telescoped casing strings. Thick filter sand packs of unknown material and/or gamma activity, and numerous repairs in the form of casing sleeves and double screened intervals also complicate interpretation.

Cased holes preclude running electric logs thus eliminating the opportunity afforded by good resistivity logs for correlation. Driller's records of these older wells are of uneven quality and some are quite incomplete. These points are raised here to show the need for good geologic supervision and open-hole geophysical logs on key, new and replacement, production wells.

Most of the large bore production wells of this area have been and presently are drilled using cable tool, drill-and-drive methods. Steel casing is driven into the ground as the hole is drilled. The tools of borehole geophysics, as they were developed by the petroleum industry, work best with mud-rotary drilling methods so that open-hole electrical logs can be run in uncased, mud-filled boreholes. Resistivity logs are an important component of the geophysical suite for water resource investigations as well. Cable-tool drilling techniques, however, do not utilize the heavy thixotropic drilling muds of rotary methods to keep the formation from collapsing into the well bore. Cave-ins are prevented by driving casing pipe as the hole is deepened. In hard rock, some wells can be deepened as open holes without driving casing. However, it is a difficult and sometimes risky task to drill open-hole with cable-tools in unconsolidated formations. Danger lies with the potential for cave-ins of the wellbore. At the very least, such cavings result in a loss of time required to redrill the caved material of the hole. In a worst case scenario, if the borehole wall collapses on top of the drilling tools, the hole and tools could be lost.

Most of the open-hole electrical and caliper logs included here were obtained only through the cooperation of cable-tool drillers who employed several techniques: 1) in order to maintain a positive hydraulic head in the borehole, a constant stream of water (15-35 gpm) was added to maintain a high water level in the well during drilling and standby time, overnight and on weekends off. This proved effective in reducing caving problems 2) not "horsing" the bailer and bit up or down the hole too fast which otherwise would have the tendency to collapse the formation into the borehole and 3) calling often for geophysical logging of short segments of the hole before driving casing. Often the logging would require multiple runs in the same well. As caving sections were encountered or anticipated, the portion of the drilled hole available would be logged open hole. Temporary or permanent casing would then be run to depth with a resumption of open hole drilling. The added costs of these techniques can be more than offset by: 1) obtaining a more efficient well with an exact and economical screen design facilitated by the geophysical logs, and 2) obtaining a less costly well in situations where logging confirms a good aquifer section is open to the uncased part of the hole. In many cases the driller would not have to weld, run, and remove temporary casing strings (or jack out the temporary casing during filter placement). Instead the driller would bail out the bottom, run liner and screens, and place filter sand.

Cuttings Analysis

The acquisition of detailed knowledge of the rocks penetrated by water wells is essential to understanding the geologic framework. Both drillers and professional geologists rarely take time to work out objective methods for the description of cuttings from water wells. One of the most useful results of this investigation is the characterization of the basin fill sediments. For this purpose, several procedures have been worked out for producing a permanent objective record, based partly upon methods of the petroleum industry (Swanson, 1981; Hulen and Sibbett, 1982; Exploration Logging Inc., 1981; McPhater and MacTieranan, 1983), but also using innovative techniques necessary for the cost-effective description of loosely consolidated clastic deposits. These cuttings analyses are included as part of the Well Logs section at the end of this document.

The grain-size percent log is an attempt to be totally objective in the description of samples. Although some of the material may be cavings, and some may be a mix of interbedded silts and sands, this objective information used with geophysical logs, gives the best possible information from a water-well drilled with conventional methods.

Samples are taken by the driller at 5 foot or 10 foot intervals during drilling. Because of the amount of time required to sample cable tool wells by bailing, cable tool wells are usually sampled after 10 feet of drilling and at formation changes. Cable tool samples are generally a slurry of the entire 10 feet of drilled section although the driller is often able to obtain a relatively undisturbed sample from the bottom of the bit as it is withdrawn from the hole before bailing. If multiple bailings are required to clear the hole, the first bailing is generally perceived to be the most representative of the drilled section. Slow emptying of the first bailer allows the best sample to be obtained just above the flap-type valve. Dart-valve bailers should be released into a slow-draining holding tank from which the sample may be taken after settling. Generally the samples are better during the drill-and-drive method because the casing is driven down as the drilling proceeds thus sealing off caving sands or swelling clays higher in the section from mixing with the representative sample. When drilling is carried out in an open borehole, closer examination of the cuttings is required in order to discount cavings from above. Mud-rotary and air-rotary drilling methods allow more frequent sampling because of the continuous flow of cuttings from the wellbore but care must be taken to discount the fines which often do not completely settle from suspension within the mud pit. Larger rigs in the petroleum industry use de-sanding units to remove fine sands from circulation. Use of "shaker tables" during rotary drilling of water-wells would improve the quality of samples.

The cuttings analysis used for this study is as follows: 100 ml of raw cuttings are washed through a stack of U.S. Standard Series sand sieves. Numbers 10, 18, 30, 50, 100, and 200 meshes are used (2.032mm, 1.015mm, 0.590mm, 0.420mm, 0.250mm, 0.149mm, 0.074mm, respectively) with a pan to catch the percentage passing through the 200 mesh sieve. The percentage of material retained on each sieve is visually estimated after being returned to the original 100 ml. graduate. Shale chips and mud lumps are then visually discounted from the sand fraction and added to the amount of material that washed through the number 200 sieve, which is reported as the silt and clay percentage. The individual fractions are totaled and, if necessary, recalculated to equal 100 percent. Such recalculations are sometimes necessary in clean, coarse-grained samples of high porosity or extremely fine-grained cuttings where some percentage of fines was lost due to suspension during the washing process.

Samples consisting of 75 percent or more silt and clay often prove too difficult and/or time consuming to wash through the sieves. For these very fine-grained specimens, a much smaller portion of raw sample (about 25 ml.) is washed through the sieves while working the sample between the fingers or with a soft bristle brush. The retained portions are viewed collectively on the screens and assigned percentages based upon visual estimates. Differentiation between silt and clay sized particles is a matter of judgement. Specimens which would remain suspended in a water column for at least one minute, or are very "sticky" with no gritty "feel" are labeled clays. These sediments have been preserved and catalogued at BSU so that a more scientific determination of clay content could be obtained were it deemed necessary.

Also, as an analysis procedure for this study, in addition to the grain-size percent log, each sample interval was examined visually and microscopically for fossils, calcareous layers, secondary mineralization, quartz/feldspar ratios, rounding, organic matter, volcanic ash, and any feature which might serve as a marker horizon for stratigraphic correlation. Color descriptions have been recorded for wet fresh samples using the Munsell Color System (Munsell, 1990).

Current methods used by engineering professionals for sand-sized sieve analyses by washing, drying, and measuring by percent weight are applicable to filter-pack design and screen-slot selection, provided good samples of aquifers are obtained. Oven drying of samples finer than sand sized particles, however, results in hardened clumps of material which must be pulverized (and so altered) to work through sieves. These techniques are time consuming (costly) and unsuitable for evaluating the entire suite of rocks represented by drill cuttings. We have found that our wet-sieving, volumetric system described above gives similar results as dry-sieving weight methods, and can also be used for filter-pack design and screen slot selection.

REGIONAL GEOLOGY

The western Snake River Plain is a northwest-trending structural graben about 40 miles wide and 160 miles long (Figure 5). Vertical throw on the bounding fault systems is in excess of 3000 feet. Other faults and basinward dip account for basin subsidence in excess of 6000 feet (Wood, 1989; Mabey, 1976). The Boise area is located along the faulted northeast margin of the plain where late Cenozoic sediment and volcanic rocks are faulted against crystalline (intrusive) rocks of the Cretaceous Idaho batholith. Downward warping and faulting of the western plain graben began 13 to 9 million years ago, accompanied by voluminous rhyolitic volcanism. Rhyolite volcanism ceased in this area about 10 million years ago. Basin subsidence continued and the lowland accumulated up to 6000 feet of lake, river, and alluvial fan sediments. The present day surface consists of fan and ephemeral stream materials, sandy gravels of flood plains of perennial streams and their older terraces, and basalt flows of the Snake River Group.

Faulting along this part of the northern margin of the western plain has diminished in activity such that the most recent faults so far detected have affected the Tenmile gravels (about 2 million years old), the Snake River Group basalts, and the gravels of the Sunrise terrace (both about 500,000 to 1 million years old). Position of the basin-bounding faults is not marked by an abrupt physiographic escarpment because younger fluvial and reworked fan deposits emanating from the mountains, as well as basalt flows, have covered the faulted margin of the plain.

Details of sedimentation and the history of the lakes that occupied the basin are poorly known. Evidence for large persistent lakes in the basin are reviewed by Jenks and

Bonnichsen (1989). They state that shoreline features occur up to elevation 3800 feet around the margins of the basin. While this is true along the northeast margin, Smith and others (1982) have found lacustrine deposits only up to elevation 3400 feet on the south side of the plain. Recession of the last major lake began about 2 million years ago and this event is marked by the Tenmile Gravel Formation, a fluvial gravel of the ancestral Boise River, that heads in the mountain front near Lucky Peak Reservoir and extends across the plain over the top of eroded and truncated lacustrine deposits (Wood and Anderson, 1981; Malde, 1987; Othberg and Burnham, 1990). Gravels following the receding lake occur down to about elevation 2900 feet in some parts of the basin (Jenks and Bonnichsen, 1989).

GEOLOGIC SETTING OF THE BOISE RIVER VALLEY

The oldest rocks of the Boise area are the granitic rocks of the mountainous area to the north of the city. Continued uplift and erosion of these rocks has supplied sediment to the basin areas south of the mountain front. About twelve million years ago, volcanic flows, showers of volcanic debris, and sediments derived from the granitic highlands and the volcanics were deposited as the Snake River basin was forming by down-faulting and downward warping accompanied by volcanic eruptions. Beneath the sediments in the northeastern part of the Boise Valley, at a depth of 1000 to 2000 feet, are layers of rhyolite volcanic rocks with fractured zones which form aquifers for scalding geothermal water up to 190° F. The geothermal aquifers are separated from the main cold-water aquifers by up to 600 feet of relatively impermeable materials comprised of altered basaltic volcanic debris and lava flows, and clayey sediment (Wood and Burnham, 1987). Overlying the basaltic section are mostly sand, silt, and clayey sedimentary rocks composed of material derived mostly from erosion of the granitic mountains. This overlying section of water-saturated sedimentary rocks constitutes the principal cold water aquifers. These rocks are included in a subdivision of geologic units of the Snake River Plain called the Idaho Group, which was deposited in the basin within the late Miocene and Pliocene epochs, over a time period from 10 million to about 2 million years ago.

Idaho Group strata consist primarily of river bed and lake bed deposits. The system of rivers and lakes in the western Snake River Plain changed many times in this time interval. Because of the shifting of river beds, floodplains, and shorelines of large and small lakes, the strata accumulated at any one point, such as encountered in a well, are a succession of alternating layers of clayey sediments of lakes and marshes, and sands and gravels of rivers and streams. For instance, the bed of the present Boise River consists of a 50 foot thickness of sand and gravel which has been laid down as a "sheet" as the river meandered over the valley. In the past, when the lake shores were near Boise, streams issuing from the mountains built sand deltas into the lake. If the lake level fell during dry periods, or because of fault movement, or because of erosion of the lake outlet, the delta sands would be built as a layer far out into the lake basin. Conversely, if the lake levels rose, mouths of streams would retreat to the edge of the highlands, and clayey lacustrine sediments would accumulate on top of the sandy delta or stream sediments. If deep water were present for a long period of time, several tens to hundreds of feet of clay and silt might be accumulated. From studies of rocks in the Boise foothills (Wood, in press; Gallegos and others,1987), it is known that at least one large lake filled much of the western Snake River Plain. Lake deposits are found in the foothills around the plain up to an elevation of about 3700 feet. However, there probably have been a succession of several major lakes that have produced the Idaho Group sediments. Reconstruction of that history is a part of ongoing scientific studies of the subsurface layers made possible by studies such as this for water resources.

During formation of the western Snake River basin, the rocks along the northeast margin were tilted and faulted downward to the west-southwest. Thus the rocks of deeper, cold-water aquifers are tilted and descend to lower elevations to the west. For this reason, successful wells in productive sand units in the updip area of central east Boise are relatively shallow (450 to 650 feet). In order to encounter the same good sands, wells further to the west-southwest, must be drilled to depths of 850 to 1000 or more feet. Wells drilled to similar depths but separated by a mile or more in the down-dip direction would generally be completed within an entirely different section. Evidence for this configuration is illustrated on the seismic section of west Boise (Figure 6). On this section the reflections from strata dip about 5° to the west. Sediment layers dipping 5° decline in elevation 460 feet per mile. Therefore, it is reasonable to expect that an aquifer at a depth of 800 feet may be at a depth of about 1260 feet one mile to the southwest. Similarly, wells situated parallel or sub-parallel to strike (perpendicular to dip) may be completed within and produce from the same aquifers. This relationship is illustrated by Profile 1 which shows the nearly horizontal continuation of the upper aquifer; sub-parallel to strike from the Hewlett-Packard well to the Goddard well on a bearing of about N60°W.

HYDROGEOLOGIC FRAMEWORK

Introduction

This chapter of the report considers the hydrogeologic framework of the uppermost 1000 feet of geologic section beneath Boise. An understanding of the three-dimensional "geometry" of this sequence of rocks which contain the waters of the Boise municipal supply is essential to realistic modeling of the system. Because any practical computer model can only be as accurate as the parameters programmed into it, a principal task of this investigation is to determine the location, thickness, and areal extent of aquifer/aquitard units in the subsurface and to provide details on the location and construction of all major production wells within the Boise area (Figure 4). Beyond the obvious need for a dimensional analysis to configure the computer model's "grid", cell size, and layering, such information is also necessary for the siting and design of aquifer testing for the purpose of deriving hydraulic properties, specifically the aquifer coefficients of transmissivity and storativity, for the aquifer system.

Based upon a compilation of drilling records, geophysical well logs, analysis of drill cuttings, and hydraulic well-test data, it is possible to broadly subdivide the Boise Valley sedimentary section into five important hydrogeologic units. Figure 7 shows the location and the areal extent of the individual units in map view. In this classification, the unit boundaries are more gradational than distinct, and it is expected that further study will result in some vertical separations and/or overlap of hydrogeologic units as well. The five major subdivisions are: 1) Boise Fan, 2) Fan-to-Lake Transition, 3) Central Boise Lacustrine Sediments, 4) Deep Artesian Lacustrine Sands and Alluvial Lake Margin Sands of West Boise 5) Lake Margin and River Sands of Northeast Boise.

The hydrogeologic units listed above are generally in order of location from east Boise to west Boise with the exception of Lake Margin Sands which appear to be a younger apron of sediments along the Boise Front. Located at the head of the Boise Valley near Lucky Peak reservoir, the Boise Fan is a large alluvial-fan and braided stream complex which resulted when a large river system exited from the mountains to the north of the plain and deposited its load. After, or perhaps during, deposition of the Boise Fan materials, large lake systems occupied the lower portions of the basin. As water was backed up in the valley, the shoreline advanced onto the fan materials. At the alluvial-fan/lake interface, fan materials were subject to "reworking" by river and lake currents combined with wind and wave energy of the shoreline environment. The Fan-to-Lake Sediments represent the transition from river (fluvial) deposits to lake (lacustrine) deposits. Basinward (west) of this transition, lake processes dominated with the deposition of sands and silts in relatively shallow water and these materials are referred to in this report as the Central Boise Lacustrine Sediments. Yet further basinward, deep-water environments of a perennial lake favored the deposition of fine silts and clays with only minor interbedded fine sands. Because the thick layers of clay and silt act as confining units for these deep sand units, this hydrogeologic setting is referred to as the Deep Artesian Lacustrine Sands of west Boise. The lake margin and river sands are interpreted as an apron of younger alluvial deposits which form a wedge-shaped sand sheet proximal to the foothills of the Boise Front. A somewhat idealistic cross-sectional profile of the subsurface hydrogeologic settings is included as Figure 8.

To some readers, the following discussions may, at times, seem far afield of the task at hand. Although the discovery, in drilling samples, of "blue" colored sediment or fossils may appear trivial, these are important indicators of ancient depositional environments. Because the water bearing qualities and distribution of aquifer units in the subsurface are solely a function of depositional systems, we are well advised to consider any and all such "clues" as important.

Geologic features pertinent to the hydrogeologic framework

Buried unconformity

In attempting to correlate strata from well-to-well, continuity is found among some units in the upper 350-400 feet (to elevations 2350 to 2400 feet) beneath central east Boise. In west Boise, continuity of units goes a bit deeper, to about 400 to 500 feet (elevation 2150 to 2250 feet). Wood and Anderson (1981, p. 24), in examining seismic sections of the Idaho Group in the Boise area, recognized that an angular unconformity probably exists at this depth between the tilted and beveled sedimentary layers of the lower Idaho Group and overlying strata that have only a slight inclination to the west. Wood (1987) recognized the unconformity about 400 feet deep (elevation 2400 feet) beneath east Boise. Angular unconformities are features that result from erosion of uplifted and inclined strata by river systems, and then a resumption of deposition and accumulation of near horizontal strata of lake beds and stream beds on top of the beveled and truncated beds. This feature of the Boise Valley is illustrated in Profiles 1, 2, 3, 4, and 10 and also on Figure 9).

A buried unconformity in the subsurface stratigraphy cannot be recognized from data obtained from a single well. The identification of such a feature depends upon reliable samples and geophysical logs from a great many wells spread over a large area.

This structure is important hydrogeologically because it indicates that deeper beds (aquifer units) are truncated upward by the unconformity surface and overlain by nearly horizontal aquifer units.

"Blue clay" and color variations in sediments:

The causes, occurrence, and importance of "blue" sands, silts, and clays of the Boise Valley, as reported on drilling records, have been widely discussed and debated for some time. To drillers, "The Blue" is synonymous with "good" water and higher artesian heads. Fresh, wet sediment samples from the bailer or blooey are indeed a deep blueish-gray hue. Munsell Color System equivalents to the driller's "blue" range from Dark gray (5Y5/2) to Dark greenish gray (5GY4/1 - 5BG4/1). These samples oxidize, almost immediately if left in the open air, and in no more than hours or a couple of days in sealed bags, to more olive and gray colors. Upon drying they also become more gray or brown. Drill cuttings more than a few hours old often do not retain the distinctive blue color. This has led to some minor confusion because drill cuttings are rarely examined by groundwater professionals before such oxidation occurs and often not before the samples have been oven-dried. Moreover, not all drillers record color changes of the drilled section. For these reasons, the occurrence of "blue" clay has been questioned and its importance downplayed.

The blue colored sediments reported by drillers are believed to be an indication of the chemically reducing depositional environments characteristic of lake deposits. Reducing conditions and concentrations of ferrous iron in solution may be present even within shallow lakes because of thermal stratification which can restrict circulation to near surface water (Livingstone, 1963). The presence of pyrite and preserved organic material within these sediments is also believed to be in support of reducing conditions associated with lake environments.

Regardless of grain-size, sorting, or mineralogical composition, most sediments of the Boise Valley are of two general colors. As observed from drill cuttings, the sediments are either yellowish brown or dark olive gray "blue". For the purposes of basin analysis the distinction is an important one. Dark gray to olive sediments were almost certainly deposited in a lacustrine environment where free oxygen is not available for oxidation of ferromagnesian minerals. From the time of deposition to the present, these dark colored reduced materials must have remained under saturated conditions to have remained in their original unoxidized state. The yellowish brown to orange brown colors are caused by oxidation of iron-bearing minerals under unsaturated conditions or by long-term circulation of oxygenated recharge waters. By the above reasoning, alluvial, fluvial, and lake margin deposits would be most likely to be oxidized and lacustrine deposits which were never exposed to desiccation, unsaturated conditions, and/or oxygenated waters would be preserved in the unoxidized state. Thus colors of sediments in the subsurface may be indicative of depositional environments. Thick monotonous sections of reduced dark colored sediments were probably deposited in a persistent lake. Thick sections of oxidized materials may be indicative of subaerial alluvial-fan and/or stream deposits. Alternating sequences of oxidized and reduced strata could represent fluctuation of water levels along a lake margin environment. One complication to the use of oxidizing and reducing conditions for "mapping" subsurface geologic contacts is described by Hem (1970); "Recharge reaching the water-table is generally oxygenated owing to contact with air, and any reduced iron minerals, especially pyrite, which the solution contacts will be attacked to yield ferrous iron and sulphate. The oxygen in the circulating water is ultimately depleted by this and other reactions, but a considerable amount of ferrous iron can be dissolved by the time the water has passed for some distance through the aquifer. Groundwater that is high in dissolved iron can be associated with the oxidation of reduced iron minerals at a regional or local contact between oxidizing and reducing conditions." Thus caution should be exercised when using color changes to interpret depositional environments. In cases where oxidation/reduction contacts are not useful for geologic interpretation, they may be diagnostic of recharge areas.

Blue clay is rare-to-absent in the extreme upper end of the valley. Occurrence of reduced sediments increases steadily in the down valley direction (northwest). The subsurface of west Boise is dominated by thick sections of blue clays, silts, and fine-grained sands. These data suggest that the basin deepened to the west.

Boundaries to the Boise aquifer system

The Boise aquifer system is limited in areal extent and depth. The sedimentary basin is bounded on the north by the crystalline rocks of the Idaho batholith where sedimentary strata lap onto or are faulted against these relatively impermeable granitic rocks. The cold-water bearing section is further truncated along the basin-bounding fault zone and other down-to-basin normal faults. The natural layering of sedimentary rocks, lateral changes in lithologies in response to fluctuating depositional patterns, and erosional features within the sedimentary sequence act as additional hydraulic barriers to the system of aquifers beneath the city of Boise. A thick section of relatively impermeable volcanic rocks form a "basement" to the cold-water bearing section (Figure 6). Occurrence of warm water at relatively shallow depth in some parts of the basin also limits the depth from which potable water can be obtained, on account of restrictions imposed by the Idaho Geothermal Resources Act of 1982.

Contact with the granitic rocks:

The sediments of the "Idaho Group" lap onto and are faulted against the granitic intrusive rocks of the Idaho batholith which forms the mountain front to the north of the city. Although these crystalline rocks are fractured and may have a somewhat permeable 'weathered zone' within the upper 50 to 200 feet, the amount of available water from these rocks is usually only sufficient to supply minimal domestic requirements. For these reasons, the exposed sediment/batholith contact, shown on Figure 1, is essentially the northern boundary to the Boise groundwater aquifers.

Faults:

In addition to the basin-bounding fault zone of the Boise Front, which truncates the lateral extent of aquifer units, other faults within the sedimentary section of the valley impede groundwater flow and limit the lateral extent of aquifer units. Many of the known and inferred faults of the Boise Valley are shown on Figures 10 and 11. One such fault, which juxtaposes Idaho Group sediments against less permeable tuffaceous clays and volcanics is located on Figures 7 and 11 and is named here the East Boise Fault. This structure has been inferred on the basis of subsurface data obtained during this study in combination with surface geologic mapping of Squires (in preparation) of the Indian Creek

Reservoir $7^1/_2$-minute quadrangle. For example, the south abutment of Barber Dam (Figure 4) is anchored in Tertiary basaltic tuffs. Thirty-five hundred feet to the northwest, the BWC East Boise Avenue test well encountered similar volcanics at a depth of 630 feet beneath land surface. Subsurface projections based on strike and dip measurements of the Barber Dam outcroppings cannot reasonably account for the 630 feet of elevation difference between these locations without some component of structural offset (faulting).

Elsewhere in the basin, faulting of the sedimentary rocks and of the underlying volcanic rocks is apparent on a seismic-section developed by the Chevron Oil Company (Figure 6). The extent to which these faults cut the sedimentary sequence above 1000 feet (elevation 1600 feet) is not presently known. Working of the gravel quarries to the south of the city has exposed minor faults which offset gravels of Tenmile ridge and of the upper Boise River terraces (Figure 11). That these deposits are faulted is significant because of the relative young age of these deposits compared to the Idaho Group sediments which comprise the deeper aquifer system. The amount of movement (offset) that has occurred along these faults and the degree to which they affect groundwater movement is poorly understood at present.

Underlying volcanic section:

Underlying the Idaho Group sediments of the Boise Valley are volcanic rocks which include basalt flows and tuffs, tuffaceous sediments, and rhyolite. This volcanic "basement" to the sedimentary section (Figure 6) forms the lower boundary of the Boise cold-water aquifer system. Most deep wells within $^1/_2$ mile of the Boise Front have encountered this volcanic section at depth (Profile 3). Fractured rhyolite of this volcanic suite form the geothermal aquifers of the Boise hot-water system (Wood and Burnham, 1983, 1987). The geothermal aquifers are separated from the cold water aquifers by a thick section of tuffaceous clays and silts of low-permeability. The basinward extent and depths to the surface of the volcanic section are not well known. Beyond $^1/_2$ mile basinward of the Boise Front, very few wells are deep enough to penetrate the deep volcanic rocks. The BWC east Boise Avenue test well (Profile 4) encountered volcanics at a depth of 630 feet below surface (elevation 2180 feet). In the fall of 1989, BWC contracted BSU geosciences to perform a seismic sounding of the Tenmile Ridge area in the vicinity of Issac's Canyon (Figure 4) for the purpose of determining the thickness of the water bearing section. These tests indicated a "strong reflector", believed to be the volcanic/sediment interface, to be present about 1100 to 1300 feet below land surface (elevation 1800 to 2000 feet) at that location (Pelton, 1989).

<u>85° F isotherm boundary:</u>

Since enactment of the 1982 Idaho Geothermal Resources Act, deep exploratory drilling for water resources has been discouraged. Because waters in excess of 85° F are restricted from use in the Boise area (Idaho Code Section 42-230), and because these "low temperature geothermal" waters are generally encountered at shallower depths than the volcanic basement, little has been learned about the deeper sedimentary section. So at present, the 85° F isotherm constitutes a regulatory boundary to the Boise drinking-water aquifers. Often associated with the granitic and volcanic rocks are geothermal waters with dissolved fluoride concentrations several times greater than is allowed under present EPA drinking water standards. The Safe Drinking Water Act of 1974 has established the limit for fluoride in drinking water at 4.0 mg/l. Fluoride concentrations within waters of the "warm" sedimentary section near the foothills faults systems only slightly exceed 4.0 mg/l and so intermixing with shallow "low fluoride" waters would reduce concentrations to below EPA limits. Geothermal water from deep wells out in the sedimentary basin, such as the Simplot Aquaculture geothermal wells near Caldwell, Idaho, are of good quality and below EPA limits for fluoride.

Subdivision of the sedimentary section into hydrogeologic units

Based upon the findings of this study, it is now possible to subdivide the water bearing sediments of the Boise Valley into distinct hydrogeologic settings (Figures 7 and 8). The five major subdivisions are: 1) Boise Fan, 2) Fan-to-Lake Transition, 3) Central Boise Lacustrine Sediments, 4) Deep Artesian Lacustrine Sands and Alluvial Lake Margin Sands of West Boise 5) Lake Margin and River Sands of Northeast Boise. A discussion of the major features of the geologic framework and of each hydrogeologic unit's location, lithology, geophysical log character, and hydrogeologic properties follows.

Boise Fan Sediments

Location and Wells

The Boise Fan sediments, within the area of study, are located within a large triangular-shaped area of the southwest Boise Valley (Figure 7). This "wedge" is bounded to the east by the East Boise Fault and extends southward beyond the study area and includes Tenmile ridge in the vicinity of the State Penitentiary, Blacks Creek Reservoir, and Tenmile Creek. The north and west boundaries are less distinct and transitional but may be located near East Amity Road and Gowen Field on the north and Pleasant Valley Road to the west. Location of wells completed within this unit and referred to in the following discussions are shown on Figure 4.

Several deep wells were drilled and completed within this hydrogeologic setting during 1990 and 1991. Samples obtained from the drillers were examined and geophysical logs were run in the BWC Columbia test well (Well Log 1), the Micron Technology Inc. production well, the Southwick domestic well, and the BWC Market Street production well. Squires, 1992, in preparation) has analyzed drill cuttings and geophysical logs for the Idaho Department of Transportation, Port of Entry well (1988). This DOT well is located on Interstate Highway 84 (I-84) near the Black's Creek exit (Well Log 2) and is also believed to be completed within Boise Fan sediments.

Results from geophysical logging and cuttings analyses of the Boise Fan area, along with well-construction data, are found on Profile 5.

Nature of Cuttings and Inferred Lithology

A conspicuous identifying feature of the Boise Fan sediment unit is the color of well cuttings. Most cuttings from this most southeastern part of the basin are yellow brown-to-reddish brown in color. The hydrous ferric oxide content of rocks is commonly responsible for their reddish to yellow color (Hem, 1970, p.114). These oxidized sediments exist in deep wells to depths of 800 to 1000 feet. Gravels are common throughout the section but organic matter, fossils, and clay layers are conspicuously absent. All this contrasts markedly with the dark-colored, blue-gray sands, silts, and clays with wood and peat detritus, which dominate the rest of the basin sediment, particularly in the west. Within the alluvial fan sediments, silty sands dominate the section, with numerous gravel lenses and a few silts (Well Logs 1 and 2). Generally, the individual grains are more angular than rounded, and most layers are poorly sorted. The base of the unit has not been characterized but drill cuttings and geophysical logs from wells 800 to 1000 feet deep (bottom-hole elevation 2150 to 1950 feet) generally indicate an overall coarsening-upwards of the section. Ethridge (1985) has interpreted such large-scale coarsening-upward cycles as reflecting growth of fans during major or persistent faulting/uplift. Typically the individual sediment layers are complexly interfingered and not laterally extensive.

Studies of drilling samples from the BWC Columbia test well (Well Log 1) show that 20 to 30 foot thick gravel beds were encountered at 80 to 100 foot intervals within the upper 550 feet of section. Data from a single well is hardly conclusive but this apparent rhythmic occurrence of gravel beds is a feature that should be watched for during drilling of future wells. Cyclic depositional patterns can be important aids for correlation and interpretation of subsurface geology.

Geophysical Log Character

Natural gamma-ray and electrical resistivity log "signatures" are unique in the Boise Fan. The logs are characterized by seemingly erratic "spikes" of high radioactivity and resistivity immediately adjoining "spikes" or intervals of low radioactivity and resistivity (Figure 12). The "spiky" log response provides support for our interpretation of the unit as having been deposited in an alluvial fan depositional environment.

High gamma-ray counts are a response to relatively high potassium content (several percent) of river gravels derived from the intrusive granitic rocks and porphyritic rocks of the Idaho batholith. Gamma-ray logs of these gravels appear anomalous because, more typically, finer grained sediments exhibit higher natural radioactivity than do coarser deposits. This is because radioactive elements, such as Potassium-40, are abundant in feldspars and micas which tend to weather readily to clays. Clays also concentrate the heavy radioactive elements through the process of ion exchange and adsorption (Keys, 1971). This "rule-of-thumb relationship between grain-size and gamma-ray response breaks down in this gravelly geologic unit. It can be seen on Well Log 1 that the radioactive levels of the gravel layers are higher than even the most fine-grained silts within the section here. Even though a general fining-downward trend is apparent from grain-size analyses this is not evident in the gamma-ray response because of the relatively high radioactivity of gravels comprised of high-potassium felsic clasts present within much of the upper section. Gravels can be distinguished from the finer grained strata on the basis of resistivity logs which clearly reflect the general fining downward of this deposit (Well Log 1). This distinction is important because the gravel beds are coarse grained with a sand matrix and are very permeable.

The fresh waters contained within the pore space of these sandy river gravels and gravelly sands are poor electrolytes with the result that resistivity measurements are high (Figure 12). Gravel-rich alluvial bars, channel lag and scour deposits, and proximal-fan sieve deposits have high natural gamma-ray counts and high electrical resistivity values. In contrast fine-to-medium grained sands are typically quartz-rich and have high resistivity values but much lower gamma counts. Silts and/or poorly-sorted silty sands of this section, probably deposited as overbank or waning flood deposits, have an intermediate gamma-ray response but low resistivity values, the low resistivity values being typical of silt and clay. Lithology controls the relative highs and lows of log response, but it is the thin discontinuous beds which impart the diagnostic spiky character to logs of wells in the Boise Fan sediments. For this same reason, detailed bed-to-bed stratigraphic correlation between wells is not possible. Still, these log "signatures" are both characteristic of and unique to this sedimentary sequence and seem to support our interpretation for these sediments as an alluvial fan deposit. Alluvial fan sediments are discontinuous and consist of complexly interfingered bed, bank, and overbank stream facies coupled with debris flow deposits. The heterogeneities of the Boise Fan are macroscopic in scale. Megascopically, the Boise Fan could be considered as "heterogeneously homogenous".

Interpretation of Boise Fan Sediments

From the aforementioned evidence, it can be concluded that these sediments represent an ancient buried alluvial fan/fan-delta system which heads along the mountain front near Lucky Peak Reservoir. This feature will be informally referred to as the "Boise Fan" in the remainder of the report. Encompassing over 50 square miles, the deposit has been drilled to depths of 800 to 1000 feet within the study area (Profile 5). Analysis of the of rocks penetrated by the BWC Columbia test well (Well Log 1) has shown these lithologies to be analogous to alluvial fan materials described in the literature by Miall,(1981) and Reading,(1978). The fan deposits are rarely exposed at the surface in the Boise Valley because of mantling by Pleistocene terrace gravels, loess, and basalt flows.

Within the area of study the Boise Fan is believed to be underlain by basalt and/or tuffaceous sediments which dip southwest and are faulted down to the southwest from the mountain front. The Columbia and east Boise Avenue test wells (BWC) encountered the buried volcanic section at 802 feet and 630 feet below surface respectively (Profiles 4 and 5). In the area west of I-84, driller's records are interpreted to indicate that the fan deposits are underlain by thicker sand units which may be lake deposits. Several deep wells (900 to 1000 feet) have been drilled in this section including those for the Yanke and Nicholson families (Figure 4) but without geophysical logs and/or drill cuttings the interpretation of the deep section is inconclusive. In an attempt to quantify the thickness of the saturated sedimentary section beneath Tenmile Ridge, two seismic soundings were conducted by Pelton (1988). He has suggested that a strong "reflector", believed to be the basalt/sediment interface, is present at approximate depths of 1100 to 1300 feet in the vicinity of Issac's Canyon (Figure 4).

Hydrogeology

The Boise Fan is an important aquifer unit which has undergone only limited development to date. Dion (1972) showed the surface of the regional water table to slope to the south and southwest at 15 to 20 feet/mile across the area of the Boise Fan aquifer (Figure 3). Because the water table descends to the south and the land surface rises in a series of terraces to the south, depth to water increases dramatically southward of the Boise River. Consequently, pumping lifts south of Amity Road and east of I-84 are 300 to 600 feet. Preliminary water level data obtained in this study (Profile 9) suggest that the local water table at present, in contrast to Dion's data, slopes to the west, presumably toward and in response to the collective pumping of Boise's production wells. The BWC Oregon Trail (1977) and Gowen (1978) wells typically produce 600 gpm and 1350 gpm, respectively from the Boise Fan. These wells are pumped continuously all year and supply about one fifth of BWC's groundwater supply during the low-demand winter season.

Boise Fan sediments are truncated to the northeast by the East Boise Fault. The location of this northwest trending normal fault is inferred from well and geophysical data (Profile 5) (Figures 10 and 11). Evidence for at least 400 to 600 feet of offset has been discussed previously in **Boundaries to the aquifer systems**. This fault is believed to juxtapose the alluvial fan deposits against impermeable volcanics and tuffaceous sediments (Profile 5). The present channel of the Boise River is incised into the relatively impermeable volcanic assemblage of the upthrown fault block. The significance of this finding is that recharge to the Boise aquifers, east (up river) of Barber Dam is limited to annual precipitation. Recharge to the basin from the Boise River is only possible below Barber Dam after the river crosses the East Boise Fault (Figure 7).

Study of drill cuttings and geophysical logs from the BWC Columbia test well (Well Log 1) and the Micron Technology Inc. 1991 production well have failed to evidence any significant confining strata. In addition, drillers did not observe rising water-levels as wells were deepened. A rise of water-level in a well when a more permeable layer is encountered during drilling is usually interpreted as an indication of confining artesian conditions. Continued measurement of water levels during drilling showed no significant rise or drop in water levels from the point at which water was first encountered. In the case of the Micron Technology Inc. 1991 production well, no significant changes in head (less 5 feet) occurred during the drilling of 600 feet of saturated sediments. This well should reflect any change in head with respect to depth because blank casing was driven to depth as drilling proceeded. By this method, water-level measurements reflect the head as a function of the position of the bottom of the casing. Furthermore, scattered water level measurements throughout the Boise Fan area showed no significant difference between water levels in relatively shallow wells and water levels of deep wells completed only within the deeper section. Although none of these indications are uniquely diagnostic of unconfined systems, collectively they strongly suggest that the upper boundary of the Boise Fan aquifer is the water-table.

Depth to water within the Boise Fan, ranges from 300 to 450 feet below land surface (Profile 5). Restrictive groundwater temperatures of 85° F and above are typically encountered in a respective range of 900 to 1100 feet below ground level in this area. Allowing for 150 feet of available drawdown (water above the pump bowls under static non-pumping conditions), these upper and lower bounds leave about 450 to 500 feet of saturated section available for production. The 1991 Micron Technology Inc. production well was drilled through 1045 feet of alluvial sediments. Drilling was stopped within rounded fluvial gravels after measurements of bottom hole temperature (using a "minimum-maximum" thermometer fixed to the bailer) revealed that the temperature was approaching 85° F. The driller's measurement of a bottom hole temperature of 83.6° F was confirmed when BSU ran a temperature log of the hole to 1045 feet below surface. This is similar to the geothermal gradient of .015° F/foot recorded in the BWC Columbia test well (Well Log 1).

Limited test data suggest relatively low specific capacity values for most of the Boise Fan aquifer (8 to 15 gpm/ft). Storativity values have not been calculated for the Boise Fan aquifer because of the lack of suitable observation wells during tests and/or because testing has not been of sufficient duration to influence observation wells.

Fan-to-Lake Transition Sediments

Location and Wells

Proximal to the Boise Fan and beneath a tract roughly bordered by the Union Pacific Gowen Spur and East Amity Road to the south, Overland Road on the north, Apple Street on the east, and indeterminate of extent to the west, are situated what we have termed the Fan-to-Lake Transition sediments. Approximate boundaries for the Fan-to-Lake transition are shown on Figure 7. Many of the most productive wells within the BWC system are completed within

these sediments. These wells include the Broadway well (2.5 million gallons per day (mgd), Vista well (1.8 mgd), Hilton Street well (2.0 mgd), Mac well (1.5 mgd), Hillcrest well (1.9 mgd), Bergeson well, BIF well, and Centennial well, all with specific capacities in excess of 12 gpm/ft (Figure 4).

Nature of Cuttings and Inferred Lithology

Fan-to-Lake sediments are characterized on driller's records as clays and sands of alternating brown and blue colors. These interfingered reduced and oxidized materials are in contrast with the Boise Fan sediments which are oxidized throughout. Another dissimilarity is the occasional presence, in drill cuttings, of organic detritus, mostly in the form of thin (less than 5 feet) shaly coal and peat seams. Organic layers were either never present within the fan materials or they were removed by oxidation processes. The geologic section, as deciphered from drill cuttings for wells in this unit, contains sands that are generally better sorted and more rounded than those of the Boise Fan materials. Individual units of sand and silt are also thicker than those of the Boise Fan.

To confirm driller's observations of alternating blue and brown colored strata, fresh cuttings from BWC's Vista Avenue, Bergeson Street, Mac, and Market Street production wells were examined in detail for this study. Strata in the Market Street well have both "fan" and "transition" characteristics. Black organic fissile shales, peat, and/or coal seams several feet thick were documented within the drill cuttings from Market Street, Vista Avenue, and Mac wells. The driller,s log for the BWC Broadway well also makes note of a two foot thick, "black hard substance" in the boring of that production well. Fine-to-coarse grained sands dominate the section and individual lithologies are generally thicker than in the "streaky" Boise Fan alluvium. Detailed grain-size analysis of drill-cuttings from the BWC Mac production well are included in Well Log 3.

Geophysical Log Character

The nature of sediments in the area of transition from alluvial-fan to lake sedimentation, noted through examination of drill cuttings, also shows up as a corresponding change in geophysical log character. In the Fan-to-Lake Transition area, the natural gamma-ray and resistivity logs have a smoother log character than the erratic and spiky character of logs from wells within the Boise Fan. The "smoothing" of log response reflects the shift from the highly changeable, dynamic influence of intermittent rivers and streams to the more stable lacustrine depositional environment. Specifically a change from thin, discontinuous flood, overbank, point bar, channel lag, cut-and-fill, floodplain and abandoned channel deposits to thicker sequences of better sorted sands, silts, and clays of the lake system. Digital, open-hole, gamma-ray and resistivity logs were run in the lower 200 feet of the BWC Mac production well (Well Log 3). Open-hole analog records were obtained from the upper 300 feet of the BWC Mac well and also from repeated runs during the drilling of the BWC Vista Avenue production well. Natural gamma-ray logs through casing, for the BWC Broadway and Bergeson production wells, have been reproduced on Profile 7. It is interpreted from these logs that individual units of predominantly sand, silt, and silty clay of 50 to 100 feet in thickness are present in the subsurface. Because thicker sedimentary units are generally more laterally extensive than thinner accumulations, it is likely that the sands and/or silty clays evident on geophysical logs from this section are continuous between wells of the Fan-to-Lake Transition. However, due to a lack of good resistivity logs and drill cuttings from this area of the city, existing data are insufficient from which to draw reliable conclusions about well-to-well correlation of strata.

Interpretation of Fan-to-Lake Sediments

Fan-to-Lake Transition sediments are interpreted to be "reworked" fan materials. As such, they have been subject to greater stream transport distance and abrasion and sorting from current and wave action of the fan/lake interface. This has resulted in better sorting of the sandy fraction with a winnowing of the fines away to basinward. The permeability of the poorly-sorted, complexly interfingered Boise Fan materials, probably has been increased by these processes.

The Fan-to-Lake Transition is an interface between subaerial and subaqueous depositional systems. Juxtaposition and/or interfingering of lake and river deposits is believed to have occurred along an advancing and retreating shoreline. Oxidized (brown) layers represent periods of low water or desiccation with the accompanying exposure to oxygenated surface and/or meteoric waters. Reduced (blue-to-gray in color) sands and clays reflect rapid burial and/or water depths sufficient to allow density/thermal layering of lake water to occur within the lake as discussed earlier in the section entitled "Blue clay and color variation in sediments".

Depositional environments along this transition varied but probably included fan-delta, fan-delta floodplain, lower or distal fan, braided stream, and near-shore lake deposits in shallow-to-intermediate water depths (no more than 100 feet). An important but unclarified issue is whether the fan and lake facies were deposited contemporaneously or if some or all of the fan materials may have predated the lake systems that occupied the basin. The following evidence favors an interpretation that the alluvial fan deposits predate the lake deposits. No thick shoreline or uniquely lacustrine deposits have been observed in outcrop or in drill cuttings from within the thick fan section. This observation holds true even at elevations where along the Boise Front numerous outcrops of shoreline and lake facies are present. This idea that the lake flooded over a pre-existing alluvial fan is further supported by the discovery by Squires (in preparation) of shoreline features (oolites) and other lake deposits in the Mayfield foothills, toward the southeast, which are correlative to similar deposits at similar elevations along the Boise Front. These outcrops are on opposite sides of the Boise Fan yet no shoreline or lake deposits are apparent at this same elevation within the fan sediments. These data suggest that at least one large lake system filled the basin, engulfing the Boise Fan and depositing shoreline facies along the foothills on both sides of the fan. The fan/lake interface upon highly erodible alluvial fan sediments probably inhibited the formation and accumulation of deltaic and/or thick shoreline deposits, as this was largely an environment where erosion occurred. Also, sedimentation delivery rates of debris flows of materials from the fan may have been great enough to drown the development of shoreline sediments.

Hydrogeology

The BWC Broadway production well, upon completion, is reported (BWC, 1971) to have been pumped at 3700 to 4000 gpm with 210 feet of drawdown after 8 hours of pumping (specific capacity = 18 gpm/ft). Well construction and completion intervals are shown on Profile 9. A second test of the well, supervised by Anderson and Kelly (1972), was conducted on July 20,1972. The well was pumped at 3000 gpm for 6 hours. Specific capacity from this test is about 17 gpm/ft. Average transmissivity and storativity values calculated by Anderson and Kelly (1972), using the Triangle Dairy and Guerdon Industries wells as observation wells, were found to be 30,000 gpd/ft (4000 $ft^{2)}$/day) and 5 X 10^{-5} respectively. The Broadway well is BWC's most productive well, pumping 1700 gpm constantly for most of the year. The BWC Vista Avenue, Mac, Hilton Street and Hillcrest production wells also are important 1100 to 1300 gpm wells which are completed within Fan-to-Lake Transition Sediments.

In 1991, BWC contracted the drilling of a new production well at Market Street and I-84. The well is located along the Boise Fan/Transition boundary (Figure 7). Drilling of the well provided important geologic and hydrogeologic data for this study. Geophysical logs were run in the hole on two separate occasions, as casing was advanced during drilling. Interpretation of geophysical logs proved to be critical in selecting screen intervals for well completion. During the completion/ pump capacity test, water levels in the pumped well and at the BWC BIF production well at a distance of 3950 feet were measured. During this constant-rate test the well was pumped at 1500 gpm for 8 hrs. Only 50 feet of drawdown occurred in the pumping well (specific capacity of 30 gpm/ft). Monitoring of the BWC BIF well showed no influence (less that 0.01 foot) from the 8 hour test. Apparent transmissivity of the aquifer(s) penetrated by the Market Street well is calculated to be 40,000 gpd/ft (5350 ft^2/day).

Central Boise Lacustrine Sediments

Location and Wells

Beneath an area which lies west of Broadway Avenue, south of Main Street, east of Cole Road, and north of Overland Road are the Central Boise Lacustrine Sediments (Figure 7). These approximate limits include the major pumping wells: Chamberlin St., Taggart St., Roosevelt St., Cliffside, Clinton St., 16th St., 13th St., Hilton St, Overland Road, Bethel St., Kirkwood St., Cassia St., Ann Morrison Park, and Julia Davis Park wells (Figure 4).

Nature of Cuttings and Inferred Lithology

In the central Boise area, cuttings from wells are characterized by having oxidized colors in the upper 200 to 300 feet and then, to total depth, entirely blue-colored sand, silt, and clay units bearing lacustrine features.

The BWC Clinton and Cassia Street production wells and the Boise Parks Department's Ann Morrison Park test and irrigation wells were drilled and completed within lacustrine sediments during 1990-91. Cuttings from both the Ann Morrison test (rotary) and production (cable tool) wells are of uneven quality. Geophysical logging data, however, are generally good (Well Log 4). Only a few samples were taken by the driller of the BWC Clinton Street production well. The best sample suite available at this time is that obtained from the BWC Cassia Street production well. Data from the drilling of the Cassia Street well are included in Well Log 5.

Most sediments obtained by drillers from deep wells in this part of the Boise Valley, have been described as blue in color. Drilling records describe the upper 200-300 feet of section as brown-to-yellow in color (oxidized) but once bluish and olive gray (unoxidized) sands, silts, or clays have been encountered, the section remains dark in color to depth. Cuttings from the Cassia Street well were found to contain black organic matter in the form of compressed plant leaves, stems, and fibrous material, iron cemented sands, and abundant pyrite. Of particular interest is the presence of a fossiliferous sand containing oolites and snail shells at a depth of 128 145 feet (elevation 2600 feet). The discovery of shoreline oolitic sand and snail fossils in the Cassia Street well is very significant because it suggests that deposits related to a large lake exist at an elevation of 2600 feet.

Oolites are a geologic facies known to be diagnostic of lake margin or shoreline deposits (Swirydczuk, 1979, 1980, 1981). These sand sized sediments are typically well-rounded and well-sorted. Such rounding and sorting is not from abrasion but rather from coating by precipitation of calcium carbonate, of a nucleus such as a sand grain or shell fragment. In the case of the Cassia Street well, the nuclei are comprised of small gastropod shells and/or shell fragments. Although numerous oolite deposits are present in the Boise foothills at elevations 3300 to 3700 feet, they have previously been recognized only once in drilling samples from wells in the Boise Valley. A similar occurrence of oolites was discovered during examination of drill cuttings from the 450 foot level (elevation 2375 feet) of the Veterans Administration Hospital geothermal re-injection well (Wood and others, 1987, Profile 6). Significance lies with the fact that if these sediments are correlative with the foothills outcroppings they have been structurally faulted and/or downwarped about 800 feet to their present position. Alternately, the vertical spread in elevation of occurrence of lake-margin features may be an indication that numerous lakes (or at least lake levels) were present during the infilling of the basin.

Also significant in the Cassia Street well is the occurrence of a 20 foot thick layer of rounded river gravels between the depths of 218 and 238 feet below land surface (elevation 2500 feet). These gravels could have been deposited in a river channel or they could be a shoreline gravel bar. Because they are overlain by predominantly lake deposits, the gravels are anomalous. Possibly they mark the erosion surface of the unconformity - formed as the most recent lake transgressed over gently dipping older deposits.

Deep Artesian Lacustrine Sands and Alluvial Lake Margin Sands of West Boise

Location and Wells

Two principal hydrogeologic settings are present in the subsurface of west Boise beneath an area that lies north of Fairview Avenue, west of Orchard Avenue, and south of State Street. The first setting consists of the upper 500 feet of nearly horizontal medium-to-coarse-grained sands interbedded with silts, and clays. The sandy fraction dominates this section and exhibits an overall coarsening-upwards grain-size trend. This area is capped by about 30 to 60 feet of terrace gravels of the Boise River. The deeper section, 500 to 1000 feet beneath land surface, consists of dipping, fine-grained, sand layers within thick sequences of clay and silt. The deepest boreholes in the area are the 975 foot deep BWC Joplin well (bottom hole elevation 1680 feet) and the 1005 foot deep BWC Goddard #1 well (bottom elevation 1655 feet). Seismic data (Figure 6) indicate that strata penetrated by these wells dip 3° to 7° to the west beyond the western edge of the study area and probably are present at depth beneath the Meridian and Caldwell areas. Dip on these sediments is believed to be a result of a combination of depositional dip, differential compaction, and structural dip from downwarping and faulting. The slope of strata amounts to 400 to 650 feet per mile. Therefore, wells spaced one mile apart along the direction of dip and completed into sand units 600 to 900 feet deep, would not be within the same sand units owing to the inclination of the strata. This relationship is shown in Figure 6 where the sands encountered near the bottom of the BWC 1967 Goddard Street well are located 400 to 500 feet below the reach of the 923 foot deep BWC Joplin well located 2 miles away in a down-dip direction. For this same reason, well-to-well correlations of strata in down-dip directions, using drilling data or geophysical logs, is usually not possible at the present well-spacing. Cross-sections drawn between wells, for the upper 500 feet of section, however, often show excellent well-to-well correlation of strata because the upper 500 feet of geologic section only dips about 2° to 3°. Such is the case for the 1991 BWC Hewlett-Packard and BWC Goddard #2 municipal supply wells (Profile 1).

Seismic Data and Dip of Strata

The Chevron Oil I-B2 seismic section (Figure 6) provides much insight into the deep sediments, volcanic basement, and structural architecture of the Boise Valley. Chevron was only interested in the deeper section, so reflection data are incomplete for the upper 1000 feet of strata, owing to their field-acquisition design. It is not known whether the tilted sands evident below 1000 feet are continuous to the near surface. Synthesis of geophysical logs for this study suggests that the deeper tilted strata do not extend to the surface but are beveled off by relatively flat lying strata above an elevation of 2100 feet (500 to 600 feet below land surface).

The upper 500 to 600 feet of sediments below west Boise appear to be distinct from the section 600 to 1000 feet below surface. Geophysical logs and drilling samples suggest good correlation of relatively flat lying strata between the 1991 BWC Goddard #2 and 1991 BWC H-P production wells (Profile 1). These wells may be located along strike and so cannot be used to determine dip for the upper layers. It is possible that the upper and lower sections here are correlative with the Pierce Gulch Sands and Terteling Springs Formation, respectively, (Burnham and Wood, in press). Further support for this hypothesis is provided by drill cuttings from water-wells of this area.

Nature of Cuttings and Inferred Lithology

The 1991 BWC Hewlett-Packard production well and the 1991 BWC Goddard Street #2 production well were drilled in this section of west Boise. Also, the Idaho Department of Transportation contracted the construction of a well for the purpose of irrigating the Broadway/Chinden Connector median/right-of-way within this hydrogeologic setting in 1991. Locations for these wells are plotted on Figure 4. Although completed at shallower depths than most of the older municipal supply wells in the area, these new wells provide valuable information on the upper 600 feet of the sedimentary section in the form of drill cuttings and geophysical logs.

The upper 600 feet of geologic section can be described from examination of drill cuttings from the 1991 BWC Goddard #2 and 1991 BWC Hewlett-Packard municipal supply wells. About 30 to 60 feet of modern river gravels mantle the surface of both the Whitney Terrace (west bench) and the present-day floodplain of the Boise River of this part of west Boise. Underlying the terrace gravels are about 200 feet of brown, poorly sorted, muddy sands and sandy silts. Between 200 feet and 550 feet below land surface, the sands become somewhat better sorted show more rounding. Color of these sediments alternate between dark gray (5Y4/1) and light yellowish brown (2.5Y6/3). Rounding of individual grains is highly variable throughout the section but both the 1991 BWC Hewlett-Packard and 1991 BWC Goddard #2 wells encountered rounded river pebbles and gravels within the last 50 feet of drilled section (Profile 1). Ten feet of gravel in a coarse sand matrix were encountered between 525 to 535 feet below ground level (elevation 2140 to 2150 feet) in the BWC Goddard #2 well. The driller's log for the older and deeper

1968 BWC Goddard #1 well, on the same site, shows a "red"-colored gravel from 568 to 583 feet below surface (elevation 2075 to 2090 feet). Gravel near the bottom of the BWC Hewlett-Packard well was noted to be 20 feet thick at depths of 670 to 690 feet below ground level (elevation 1960 to 1980 feet).

No wells were drilled below elevation 1960 feet in this part of the basin during this study so deep sediment samples are not available for examination. According to drillers of some of the deeper wells in the area, the lowermost sands are fine and "cleaner" than sands of the upper section and that the clays are more compressed or compacted than clays and silts of the upper 500 feet. Driller's logs from the deeper wells also record a change in color of the sediment around this same elevation. Drillers record alternating dark gray and light brown colors for the upper 500 to 600 feet of sediments, but note only dark "blue"- colored strata below elevation 2100 feet.

Geophysical Log Character

Resistivity and natural gamma-ray geophysical logs were run in the 1991 BWC Goddard #2 well, 1991 BWC H-P well, and 1991 DOT #1 Broadway/Chinden Connector well. Cross-sections through these wells are shown in Profile 1. Natural gamma-ray logs were run in the cased BWC Bali-hai, BWC Frontier, and BWC Goddard #1 production wells (Profile 7) during maintenance periods when the pumps had been removed.

Resistivity and natural gamma-ray logs of the upper 200 feet of geologic section in this area show the characteristic erratic and spiky signatures of alluvial/fluvial sediments. Below this section, log response indicates thicker, more uniform layering of materials. Steady increases and/or decreases in radioactivity and spontaneous electric potential, as recorded on geophysical logs, suggest gradual and gradational geologic changes in sediment grain-size. Coarsening upwards sequences (up to 150 feet thick) grade from thick monotonous clay and silt units (high gamma - low resistivity) of the deeper-water lacustrine system (prodelta silts) upward to units of sandy silt and fine sand. The clay and silt units are punctuated by abrupt thin sand lenses (low gamma - high resistivity). These changes, shown in Profile 1, compare with those of a lacustrine delta system described by Wood (in press) .

Interpretation of West Boise Sediments

Geological interpretation of these subsurface data is possible when viewed in light of ongoing geologic studies and mapping of field relations in the foothills north of Boise. The deep section (below elevation 2100 feet) of "blue", well-sorted, and tilted strata is believed to consist of sediments of a large persistent lake which occupied the basin. The occurrence of gravels and brown or red-colored sediments is evidence of partial draining of the lake in the Boise area. The deep river gravels encountered near the bottoms of the 1991 BWC Goddard #2 and 1991 BWC Hewlett-Packard production wells and the "red" gravels reported by the driller at a similar elevation during the drilling of the 1967 BWC Goddard #1 well, probably represent river deposits following the receding lakeshore out onto the newly exposed lake bed. After partial recession of the lake, meandering river channels and floodplains formed over lake deposits.

Alluvial fans emanating from drainages of the granitic highlands to the north began to build out onto the exposed lake bed and delta plain. As these fans from the many drainages of the Boise Front continued to grow, they eventually coalesced into an alluvial apron extending out over the exposed lake deposits and into the lake which was now occupying a lower level in the basin. Abundant evidence for such an alluvial apron does exist along the foothills exposures north of Boise (Will Burnham, 1991) and probably represents an intermediate stage between the waning of lake systems and the present-day erosional features.

The alternating dark gray ("blue") and light brown colors of sediments 200 to 500 feet below the surface of what is now west Boise are believed to represent fluctuations of lake level over time. Dark colored, unoxidized layers represent periods of inundation during higher lake levels. Brown oxidized strata mark periods of desiccation which occurred during lower stands of the lake. As lake levels lowered, previously deposited lake margin and lake bed materials to be exposed to erosion to be redistributed. At some point, the lake completely drained from the valley, and brown-colored, poorly-sorted alluvial fan materials built out away from the mountain front as a wedge-shaped sand sheet thinning to basinward. This sand "sheet" is represented in drill cuttings by about 200 feet of brown, poorly sorted, muddy sands and sandy silts which underlie the 40 to 50 feet of modern river gravels.

Hydrogeology

Most municipal production wells in west Boise produce between 1000 and 1500 gpm). It has been relatively easy for drillers to complete wells in this section because of the marked contrast between thick blue silts and clays and the clean well-sorted sands. Drillers have recognized increases in hydraulic head of 30 to 40 feet when these artesian sands are pierced during drilling. Water-level measurements, taken in existing wells of different depths and in drilled wells as they were deepened suggest that west Boise is a groundwater discharge area. Groundwater discharge areas are characterized by increasing head-potential with depth (deeper wells yield higher heads) and upward flow gradients (flow towards the water-table). For example, the 1967 BWC Goddard #1 production well, which is open only to formations below elevation 1900 feet, is an artesian-flowing well during part of the year. The heads of deep aquifers (below 1900 feet elevation) of west Boise are several-to-ten feet above land surface (2660 feet elevation) in the spring of the year. The 1991 BWC Goddard #2 production well at the same site, which is completed higher in the section between elevations 2100-2200 feet, has a static water level of 40 feet below ground level. It is probable that a well at the same site, open to aquifers which are deeper than those encountered by 1967 BWC Goddard #1, would have even greater pressure head.

Production wells which are open to 80 to 100 feet of formation and completed with continuous wire-wound screen and filter-packed, generally experience drawdown of 150 to 200 feet when pumped at 1000 gpm. Presently, because of a lack of quantitative test data, it is not known whether these relatively large drawdowns are due to inefficient well completion (well loss), lower hydraulic conductivity values, or both. However, the deep aquifers under west Boise are semi-confined and, indeed, are under the greatest degree of confinement that exists beneath Boise.

The thickness and fine-grained nature of the aquitards under west Boise (as judged from cuttings and well logs) suggest that these strata form confining layers. The pressures in these aquifers are probably created by hydraulic head provided by flood irrigation and seepage from canals on the benches of the Boise River and by infiltration of the Boise

River in the east Boise area; ie. flowing artesian wells probably did not exist prior to the turn of the century.

Figure 6 suggests that the west Boise deep artesian aquifers should be truncated to the north or northeast by down-to-basin normal faults such as the West Boise/Eagle Fault and/or beveled off updip by an erosional angular unconformity (Figures 9 and 10). Virtually all well-completion/pump-capacity tests of production wells in this region have shown indications of such negative hydraulic boundaries in the subsurface. Negative hydraulic boundaries have the effect of steepening the slope of standard semi-log time/drawdown plots (Figure 13).

Lake Margin Sands of Northeast Boise

Location and Wells

Lake margin sands and silts of the upper Idaho Group are located in the subsurface of an area bounded by the Boise foothills on the northeast, Boise Avenue to the southeast, Eckert Road to the east, and Capital Boulevard to the west (Figure 7). Geologic documentation of the subsurface for this part of Boise is better than most other areas. This is partly due to good geologic data obtained during the drilling of the city and state geothermal wells and because many of the cold water wells here have been geophysically logged. Drilling sample analysis and well testing conducted by BSU in this area also provides data about the subsurface geology.

Major production wells believed to be completed within this hydrogeologic setting include; the BWC Longmeadow, Mountain View, Marden Lane, River Run, Logger, and Centennial wells. Mesa Water Corporation's #1 and #2 production wells are also completed within these aquifers. The Capital Mall, Veterans Administration, Boise Park's Quarry View, and Yanke/Kanta geothermal wells penetrate this section but are not open to the cold-water bearing section. Locations for these wells are plotted on Figure 4.

Nature of Cuttings and Inferred Lithology

Samples obtained by the driller from the BWC Longmeadow #2 production well (Well Log 6), the BWC River Run test well, and the Boise Parks Department's Memorial Park irrigation well (Well Log 7) were analyzed. In general the sands and gravels obtained from these wells appear to be "clean" (free of fines) and well sorted. The less permeable semi-confining layers are more silty than clayey and probably have measurable cross-bed permeability (leakage).

These deposits have been interpreted as lake margin facies by: 1) comparison to similar deposits exposed along the Boise Front, 2) by their location along the faulted margin of the western Snake River Plain, 3) repeated instances of carbonized wood fragments within cuttings from the sandy sections, 4) the well sorted nature of many of the sand layers, and 5) interbedded fluvial deposits including rounded gravels.

Geologic Framework

Deep wells (below 2200 feet elevation) in this part of the Boise Valley have invariably encountered volcanic rocks, high water temperatures, and relatively high fluoride concentrations. Very few wells have been drilled to this depth beyond 1/2 mile basinward from the mountain front. The BWC Beacon Street well may be close to piercing volcanic rocks and the well does exhibit elevated fluoride levels (4.53 mg/l) as does the River Run production well (1.03 mg/l). Fluoride-bearing waters of the Boise area are believed to have been in contact with silicic volcanics which contain fluoride-bearing minerals. Bottom hole temperatures measured in these wells were not unusually high; 65° F and 69° F respectively. Seismic reflection data obtained by Kleinschmidt (1989) and Kleinschmidt and Pelton (1989a, 1989b) show that a "strong reflector", believed to be the volcanic/sediment interface, is present at about elevation 2000 feet (Profile 4). The basinward extent of these basalt and rhyolite flows and tuffs is presently unknown.

Stratified sediments, based upon geophysical log character, correlate convincingly within the upper 400 to 500 feet or generally above elevation 2400 feet. Interpreted in geologic cross-section (Profile 4) these strata appear to be relatively flat lying, layered and laterally continuous. The nearly horizontal attitudes of these sand units may indicate that these sediments have not been greatly deformed by faulting / downwarping of the basin.

It is certain that these basin margin aquifers are truncated by faulting and/or by the unconformity with less permeable granitic and volcanic rocks along the mountain front to the north. The existence of these faults, with total offset of about 800 to 1200 feet, has been suggested on the basis of geological field mapping along the Boise Front (Burnham and Wood, in press) and drilling and geophysical data obtained from the geothermal wells (Wood and Burnham, 1987; Burnham and Wood, 1983). During the drilling of several of the Boise geothermal wells, the elevations at which correlative litho-stratigraphic units were encountered were found to be so different over relatively short distances that it is nearly impossible to explain without introducing some element of structural offset. Hydraulic boundaries, which have become apparent during virtually all well testing in this section, have been attributed to the marginal fault zone (Scanlan, 1988).

Hydrogeology

Despite the hydraulic boundaries of the frontal fault zone, the relatively shallow volcanic basement, and pronounced interference between wells, the wells of this part of town produce 500 to 1500 gpm consistently over the pumping season. This is indicative of a relatively transmissive section. Initial apparent transmissivity values (short-term/near well) for these wells typically fall within the range from 45,000 gpd/ft to 62,000 gpd/ft with values as high as 90,000 gpd/ft reported (J.M. Montgomery, 1988; Scanlan, 1989).

Aquifer testing with the assistance of Boise Water Corporation and Mesa Water Corporation (Longmeadow, River Run, and Wise #2 well tests) have shown most of the wells in this area to influence one another. Qualitative results of the Wise #2 well test are presented in Figure 14. Specifically, the Longmeadow, Mountain View, Marden Lane, Logger, River Run, Quarryview Park, and Wise #2 wells can be shown to have some degree of hydraulic connection. This is to say that pumping of any of the above wells will result in some component of water-level decline in each of the other wells after an amount of time which is directly related to the distances between wells. Hydraulic connection across the Boise River to the south, to the Londoner and Beacon Street BWC wells, is less certain. Well interference data presented in Figure 14 provide support for correlation of sand units as shown on Profile 3.

CONCLUSIONS AND RECOMMENDATIONS

Recharge

Conclusion:

The primary sources of recharge to the Boise aquifer system are the Boise River and present day, diversion canals and their laterals, and from flood irrigation of the river terraces to the south of the river. Increased groundwater withdrawals combined with canal leakage, flood irrigation, and septic discharge, commensurate with population growth, have possibly accelerated these recharge mechanisms by increasing vertical hydraulic gradients. However, urban development of irrigated agricultural land and lining of the larger canals is beginning to cause a gradual decrease in the amount of water available as recharge to groundwater reservoirs. Future urbanization and canal-lining will continue to decrease recharge to the groundwater system.

Increased withdrawal coupled with decreased replenishment will eventually lead to water level declines. This study documents that water levels in wells in parts of the southeast Boise area have declined at least 40 feet over the last 20 years (Profile 6). While the 40-foot decline in parts of southeast Boise has not created any major problems to date, further lowering of the water-table and piezometric levels in confined aquifers could produce undesirable effects. The effects are: 1) increased pumping lifts caused by decreasing water levels in wells, 2) possibly drying up existing wells that were not constructed with enough depth below the water-table to permit mitigation by lowering of pumps, and 3) compaction of clayey beds in response to lowering of pore-water pressure. Such compaction of aquifers can cause loss of aquifer storage capacity and, in extreme cases, result in land-surface subsidence (Poland and Davis, 1969).

Recommendations:

1). Artificial recharge: To compensate for reductions in recharge to the groundwater system and to ensure the maximum amount of available water for future growth, the feasibility of artificial recharge to the Boise Fan aquifer should be investigated. Because the unsaturated zone in this vicinity is thick, porous, and permeable, there is great storage potential. Sources of supply for such a project might include: 1) the acquisition of water rights of irrigation districts and agricultural lands as they are urbanized, 2) any unappropriated "excess" water due to storms and spring runoff, and 3) the purchase of storage water from Lucky Peak, Arrowrock, or Anderson Ranch reservoirs.

Boise River water could be used to artificially recharge the Boise Fan aquifer unit, at the head of the sedimentary basin, west of the East Boise Fault and south of the river. This has already occurred to some extent via the unlined parts of the diversion canals. Transport of water from the sources (Boise River or Lucky Peak Reservoir) to injection wells along the upper region of the Boise Fan just below Lucky Peak dam is not a difficult engineering problem. Utilization of the Boise Fan as a subsurface reservoir would minimize evaporative losses and the need for a surface distribution system; both of which are drawbacks to the present reservoir system.

Both injection and surface application methods should be considered. Injection of recharge has merit for the following reasons: 1) injection would minimize the amount of land required, 2) the water could be injected within or below the surface basalt flows and especially below caliche "hardpan" which is relatively impermeable in this area, 3) frozen loess soils could restrict infiltration from surface application in spring when seasonal runoff may be available, 4) surface land area would remain available for development, 5) the sage desert ecosystem would not be affected, and 6) because the Boise Fan area is a natural recharge area, there is probably not a significant difference between the water chemistry of the natural groundwater and the water to be injected (differences in chemistry of injected water and natural groundwater have caused mineral precipitation problems in some artificial recharge projects). Surface application merits include: 1) surface infiltration ponds could act as temporary storage reservoirs for unappropriated spring flood runoff. Such ponding could facilitate the capture of voluminous but short-lived spring and/or storm runoff events, 2) land application reduces problems associated with injection well maintenance, 3) a large-scale project could add to flood-control protection for the city of Boise.

A study to evaluate cost versus benefit would involve drilling of several small diameter (6-inch), 500 to 1000 foot water level monitoring wells and a 100 to 400 foot deep test injection well. Drilling of 6-inch monitoring wells would provide the necessary information on the subsurface geologic framework. Hydraulic testing of these wells could provide estimates of storage volume available. These studies are prerequisites to evaluating the ability to recover recharge water and cost versus benefit of such a project. If sufficient water rights are obtainable, the long-term cost/benefit ratio should be favorable.

2). Geochemical study: A better understanding of the recharge to the aquifer system could be obtained by examining the downward movement of anthropogenic chemical constituents that have been introduced throughout the world into surface waters during this century. Such a study would examine for tritium (produced by thermonuclear weapons testing in the atmosphere in the 1950's) and for fluorocarbons (introduced into the atmosphere by industrial processes since about 1940). Water from wells at successively greater depths should be analyzed in areas of suspected recharge, and where vertical hydraulic gradients and the geologic framework are well known. These data would give a measure of the rate of groundwater percolation from the shallow gravel (water table) aquifers into the underlying section of semi-confined aquifers. Connection is either across an angular unconformity, by interconnection of sand bodies on account of discontinuous aquitards, or by vertical leakage across silty aquitards. Results of this study will serve as a check on the computer-model derived recharge estimate, and also provide an understanding of the susceptibility of the deep aquifers to pollution from surface sources of hazardous materials.

Well construction (well-head protection)

Conclusion:

Perhaps one of the most serious threats to the Boise area water supply lies with the primary hydraulic structures (wells) through which it is drawn. Improper construction and completion methods for past and present wells provide conduits for contaminant migration.

The surface-seal provided by casing, with driveshoe, driven into a fine sediment layer of low permeability may provide the best possible seal from potentially contaminated waters of the surface gravel aquifer. Cable-tool drill-and-drive methods, where casing and driveshoe are driven as the well is deepened, may provide a better protective seal between the formation and casing than current grouting techniques for overbored cable-tool-drilled wells. Surface-seals formed by pumping cement or bentonite grout from the bottom, or though gravity feed from the top are not easily verified and such seals may not be adequate. Problems with cement/bentonite grout lies with the relatively "thin" nature of these materials at viscosities that can be readily pumped. Without some component of granular matrix to provide structural integrity, bentonite drilling-fluid or cement grout may be susceptible to dilution from formation waters and/or settling. Cement grout alone is not an effective sealing agent because of its tendency to shrink and crack upon curing. In rotary-drilled wells of sufficient overbore (formation/casing annulus greater than 3-inches), dehydrated bentonite granules may be "tremied" into place at key locations or if water is used as a drilling-fluid, pelletized bentonite may be dropped into place through the water-column. The gravel-packed annulus of overbored wells provides a conduit for vertical migration of contaminants, and attention should be given to establishing seals in the gravel-pack between major aquifers.

Depth of sealed surface casing should be based upon site geology and not a fixed length as the 18-foot surface casing presently required by Idaho state law. In most locations in the Boise Valley, 40 to 60 feet of river floodplain gravels are present at the surface and the waters of this uppermost aquifer are known to be locally polluted with a variety of contaminants. Eighteen feet of surface casing would do little to seal a deep well from contaminated shallow groundwater.

Attention to better well construction, and in particular to improved sealing techniques, is needed now to prevent the wellbore annulus, the filter-pack, or the wellbore from forming a conduit for contaminant transport. If the wellbore annulus is not sealed, or if the entire formation/casing annulus is filter-packed: 1) it is difficult if not impossible to determine which open interval of the well the contamination is in and 2) even if the well is abandoned by filling in with concrete or bentonite, the contamination is still able to move between different aquifers via the filter-packed annulus. Even in formations (such as the Boise Fan) where aquifer units may not be separated by thick aquitards, intraformation seals should be placed between screened intervals to ensure that the vertical hydraulic conductivity of the wellbore annulus is no greater that the cross-bed permeability of the formation materials.

Recommendations:

1). Surface seals, and intermediate and pump-chamber casing: In order to obtain an adequate surface seal from potentially contaminated surface and shallow aquifer waters, overbored wells should be drilled to surface-seal depth and then bentonite-based grout should be pumped from the bottom of the surface casing until it appears in the overbore/surface-casing annulus at the surface. Once the formation/casing annulus is filled with grout, the surface casing should be driven into the low permeability sediment to seal the well. Surface seals can easily be verified by raising or lowering of the water-level in the casing and observing the altered level for a time.

2). Intraformation seals. In gravel pack wells, bentonite seals should be placed within the annulus between casing and formation to separate aquifer units and to prevent cross-contamination transport through the gravel pack or voids in the annular space of the wellbore. All efforts should be made to not compromise the natural stratigraphic layering which provides resistance to contaminant transport.

Groundwater Resource Database

Conclusion:

The present hydrogeological data-base for the Boise area is limited and is inadequate as a foundation upon which to base resource management policy. This void has been recognized by local governmental committees addressing the water resource issue. For example, the Water Committee for the Ada Planning Association's "Boise Visions" project (1991) have included the following among their most urgent recommendations: "Begin now the long-term evaluations and database development necessary to preserve supply sources, supply line routing and protection, and establishment of coordinated management plans." and "Additional studies are needed to fully characterize the groundwater system including its hydrogeology, water-yield, and areas of vulnerability."

Although there have been many qualified individuals who have carried out investigative work in this part of the western Snake River Plain (see **Previous Investigators**), the measured record, in terms of the length of time over which we have been developing the water resource, is poor. This is primarily because trained geologists and/or trained technical persons have had only limited involvement in the resource development process. Drilling reports, on which we are dependent for most of our information, are generally of poor quality and are very subjective. Most measurements of water-levels in wells, as recorded on driller's reports, are questionable. Except for a few long-term water-level records of U.S. Geological Survey observation wells, reliable historical water-level data are spotty and only available for scattered locations.

Recommendations:

1). Changes to the State of Idaho Well Driller's Report. Redesign the State of Idaho Well Driller's Report form to include: 1) water level measurements as the well is deepened, 2) color of cuttings, 3) sections of the hole drilled "open", 4) caving formations, 5) description, origin, and placement of gravel packs, seals, fill, etc., and 6) sketches of packer assemblies or fabricated custom components. These changes might be best accomplished by requiring two separate forms; one for drilling data and a second for completion data. Knowledge of the details of well construction are essential to the assessment and remediation of groundwater contamination problems.

2). Develop and preserve a network of monitoring wells. Except for water-level monitoring carried out by the U.S Geological Survey under long-term cooperative and special programs, long term records of Boise Valley water-levels do not exist. If such data were available, more would be known about changes that have been induced within the groundwater system. For example, at the turn of the last century, the Boise area groundwater regime existed in a natural state of equilibrium. Diversion of the river for agricultural irrigation has altered the natural recharge and caused water levels to rise in certain areas. A second major alteration to the natural state began with the development of groundwater resources for irrigation, industrial, and municipal supply. Urban sprawl and the subsequent decline in flood irrigation now constitutes a third effect on the groundwater of the Boise area. Long term water-level measurements throughout the last 80 years would have shown the magnitude of such changes to the groundwater system. Separation of the effects of these changes without historical water level trends is extremely difficult.

Monitoring of water levels in wells should resume/begin immediately as a barometer on the "health" of the groundwater system. Needed is a network of about 10 permanent water-level observation wells positioned at key locations within different hydrogeologic settings. Certain existing wells to be abandoned, abandoned wells, and test wells could be instrumented as monitoring stations. New exploratory test wells could be designed to serve as observation wells rather than be filled in.

3). Require geophysical logging of certain wells. Because lithologic descriptions by drillers cannot be totally relied upon for engineering considerations, geophysical logging of certain water wells should be required. Geophysical logs provide a vital record of a water well and should become a standard practice in Idaho for completion design and as an objective record of lithology and other conditions in the well. Wells required to be logged should include but not necessarily be limited to: 1) municipal supply wells, 2) all injection wells, 3) wells deeper than 300 feet, and 4) wells to be abandoned. These requirements could be established by amendments to the various state codes concerning water and wells or by directives from the director of the Idaho Department of Water Resources.

Current geophysical research has developed methods and instruments for verification of monitoring-well construction (Yearsly and others, 1991). Logs are now available that can detect: 1) the location and competency of annular seals and/or filter packs, 2) size, position, and condition of casing, 3) locations of screens, perforations, and/or corrosion, 4) flow within the well bore (intermixing of aquifers), and 5) voids or cavities in the borehole wall. With proper instrumentation and interpretation, most of these features of well construction can be determined using existing technology.

Most driller's appreciate geophysical logging because it helps them to complete a better water well. Logs provide a check of a driller's own interpretation of subsurface conditions which cannot directly be observed, thus increasing his/her confidence in their interpretation. Additionally, drilling contractors value logs as a means to help explain subsurface conditions to customers.

Protective clay layer

Conclusion:

There is presently a widely held belief that a protective clay layer exists between the surface (locally contaminated) aquifer and the deeper municipal supply aquifers. This valley-wide clay "blanket" has been mentioned in numerous professional reports and espoused publicly by various government agencies. Such a protective layer does not exist in the Boise area. Although low-permeability units do underlie the surface gravel aquifers at some locations, there is no evidence to support continuity of such a unit over any extensive area. In many more cases the opposite scenario is true. Instead of a protective clay layer, the sands of the Idaho Group of formations (which comprise the Boise aquifer system) are overlain directly by a highly permeable "sheet" of floodplain gravels of the ancestral and modern-day Boise River. This is to say that at many locations, a hydraulic connection between surface aquifers and deeper municipal-supply aquifers exists that will allow free communication of contaminated surface waters to the deeper system. For this reason, whatever is dumped or spilled onto the ground now may eventually be detected in the water-supply of the deeper system.

Recommendations:

1). Begin groundwater pollution awareness campaign: Groundwater constitutes over 90 per cent of the municipal water supply for Boise Idaho. This is not because groundwater is more economical than treated surface water but rather because surface water is not available in sufficient quantity to satisfy demand. Contamination of our subsurface intermediate-to-deep aquifer units will have severe impact upon the growth potential of the Boise area. Remediation studies and treatment of deep aquifer water will place substantial burdens on the tax-base. For these reasons, it is recommended that public pollution awareness campaigns be initiated now by public utilities, state and local governments, and regulatory agencies. Such public service messages should be disseminated throughout the media and in schools in order to reach the broadest spectrum of the public possible.

Improved methods

Conclusion:

Hydrogeologic supervision of new wells, as a course of this study, has; increased well efficiency, improved well yield, curbed completion costs significantly, and provided the best data presently available for the Boise hydrogeology. By increasing well efficiency, electrical power costs of pumping are reduced as are well-maintenance costs associated with screen-encrustation problems. Improved well yields have reduced the number of wells needed to supply demand. Borehole geophysical techniques have also proved cost effective by: 1) accurately locating permeable aquifer units, 2) facilitating accurate positioning of screened sections, and 3) by significantly reducing the amount of screen installed in a well. Development of open-hole drilling techniques, necessary to electrical geophysical logging, has further reduced drilling costs by eliminating the need to run temporary casing and by saving time required to pull or "jack" temporary casing. Perhaps the greatest benefits, in terms of economics, are yet to be realized when this database is used to predict contaminant migration, designing remediation projects, vary pumping schedules to control spread of contaminant plumes, and as a management tool to avoid over-appropriation of the groundwater resource.

Recommendation

1). Continue hydrogeologic supervision of drilling and well-design: For the above reasons and to ensure the most accurate and up-to-date model of the Boise aquifer system, the procedures of this first-year study should be continued. Specifically, visitation of drilling sites, discussions with drillers, collection and examination of drill cuttings, and geophysical logging of wells are essential prerequisites to groundwater basin analysis.

Supply

Conclusion:

The possibility of a municipal water shortage within the next 20 years exists because: 1) the rapid population growth which Boise is presently experiencing is expected to continue into the next century, 2) the groundwater reservoir for the Boise supply exists only beneath the city and so is more susceptible to contamination by urban activity than if the basin were located at some distance up-gradient under undeveloped land, and 3) urbanization of flood-irrigated agricultural land is decreasing the amount of recharge available to the deep aquifer system.

By drawing large quantities of high-quality deep-aquifer water for low-quality uses (irrigation, car-washes, fire-protection, etc.), we are increasing recharge gradients between the shallow and deep systems unnecessarily and increasing the risk of inducing contaminants to move downward into the deep system.

Recommendations:

1). Prioritize the uses for our pristine deep-aquifer waters.

2). Consider a dual-distribution system: Admittedly, a dual distribution system goes hand-in-hand with a plethora of economic, logistical, and public health concerns. The possible alternative of having to treat all of our groundwater, however, warrants this consideration. For irrigation of park-lands, playing-fields, lawns, cemeteries, and golf courses; shallow groundwater sources should be utilized. Newly developed subdivisions should install shallow-well irrigation systems for lawn-watering purposes. In some areas of the city (modern Boise River floodplain) groundwater is shallow enough that low-cost shallow wells could be drilled for irrigation purposes. Individuals and/or small "associations" should be encouraged to install such shallow wells which would essentially recirculate the lower-quality shallow groundwater.

3). Water conservation: Place emphasis on drought-tolerant landscape architecture for all governmental properties. Offer incentives for; 1) conversion of existing commercial and private landscaping to Xeriscape, 2) installation of water-saving plumbing fixtures, and 3) for low volume use.

4). Explore for new aquifers: The present well-density of the developed portions of the Boise area is such that further development will result in pronounced interference effects between large production wells. There appears, however, to be portions of the

Boise area which have development potential but which have not been explored for production well potential. It is recommended that an exploratory test well be drilled in Sections 10 or 11, T.2N., R.2E. near Tenmile ridge. Needed are data on 1) the thickness and permeability of the deep saturated section, 2) the temperature and quality of the deeper waters, and 3) the depth and extent of the volcanic "basement". Such a well could provide information for the development of a well field within Sections 1 through 13, T.2N., R.2E. and Section 34, T.3N., R.2E. of south Boise. Although pump lifts may be 200 to 400 feet, elevation of the area would provide gravity head for the delivery system.

Certain locations of the Barber Flat area of east Boise should be explored by drilling to determine the thickness of the cold-water bearing section and to investigate the existence of deeper aquifer units below, and separated from, the Boise River surface gravels. This area has not been explored for supplies, although several domestic wells have produced good quality water. It is important to site as far south as possible in order to avoid shallow geothermal water along the mountain front.

Hydraulic interconnection of aquifer units

Conclusion:

Based upon our geological and geophysical investigations and also upon preliminary hydraulic testing, the Boise aquifer system appears to behave as a very leaky artesian system. We have broadly subdivided the water-bearing section into major hydrogeologic settings on the basis of distinct differences in rock-type, depositional environment, and hydraulic characteristics. In some instances, there is a basis for further partitioning into separate aquifer units but the boundaries between aquifer units and hydrogeologic settings are gradational such that hydraulic continuity exists across the system. Below east Boise, this hydraulic interconnection is most direct and inter-aquifer leakage is measurable over relatively short pumping periods. The subsurface of west Boise has the greatest degree of separation between aquifer units and leakage is more difficult to measure.

Extent of the Boise Aquifer

Conclusion:

The Boise aquifer system is limited in areal extent and depth. The sedimentary basin is bounded on the north by the crystalline rocks of the Idaho batholith where sedimentary strata lap onto or are faulted against these relatively impermeable granitic rocks. The cold water-bearing section is further truncated along the basin-bounding fault zone and other down-to-basin normal faults.

A thick section of relatively impermeable volcanic rocks underlie the basin-fill sediments which comprise the aquifer/aquitard system beneath Boise (Figure 6). Where this volcanic assemblage is present within 1000 feet of the present-day surface, it forms a "basement" to the cold water-bearing section. Elsewhere in the basin, even at locations where thousands of feet of saturated sediments are present, low-temperature geothermal waters (greater than 85° F) are typically encountered at depths of 1100 to 1300 feet owing to the natural geothermal gradient. Occurrence of these warm water at relatively shallow depth also limits the depth from which potable water can be obtained, on account of restrictions imposed by the Idaho Geothermal Resources Act of 1982.

Recommendation:

Reconsider the restrictions on the use of potable waters carrying temperatures in excess of 85° F. Such consideration is especially applicable to the groundwaters of the deeper basin, beneath west Boise, because there is very little likely connection between the deep-basin aquifers and the geothermal aquifers of the Boise Front fault zone.

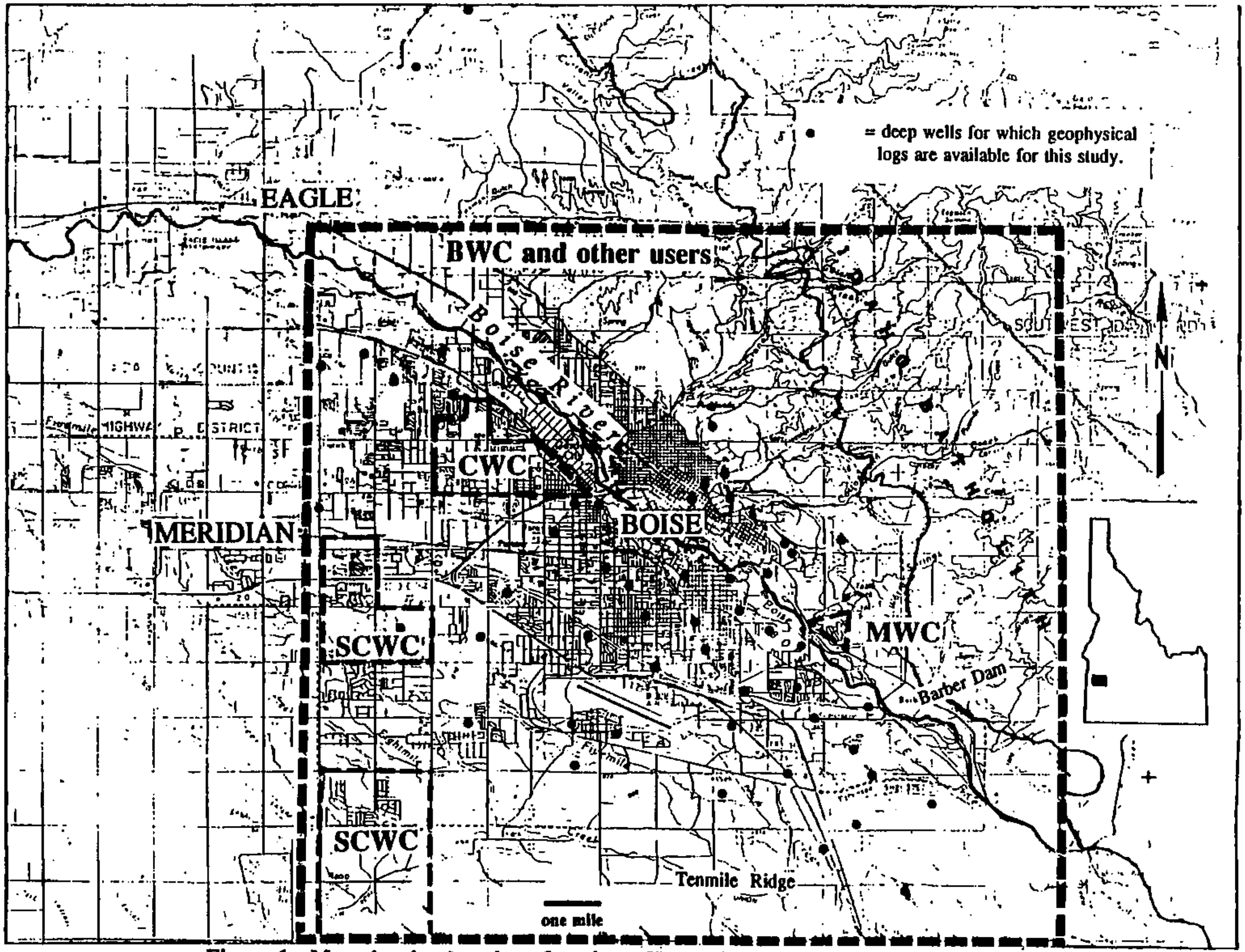


Figure 1. Map showing location of project. Heavy line is the approximate perimeter of the service area for Boise Water Corporation (BWC & other users). SCWC = South County Water Company, MWC = Mesa Water Corp., CWC = Capital Water Corp.

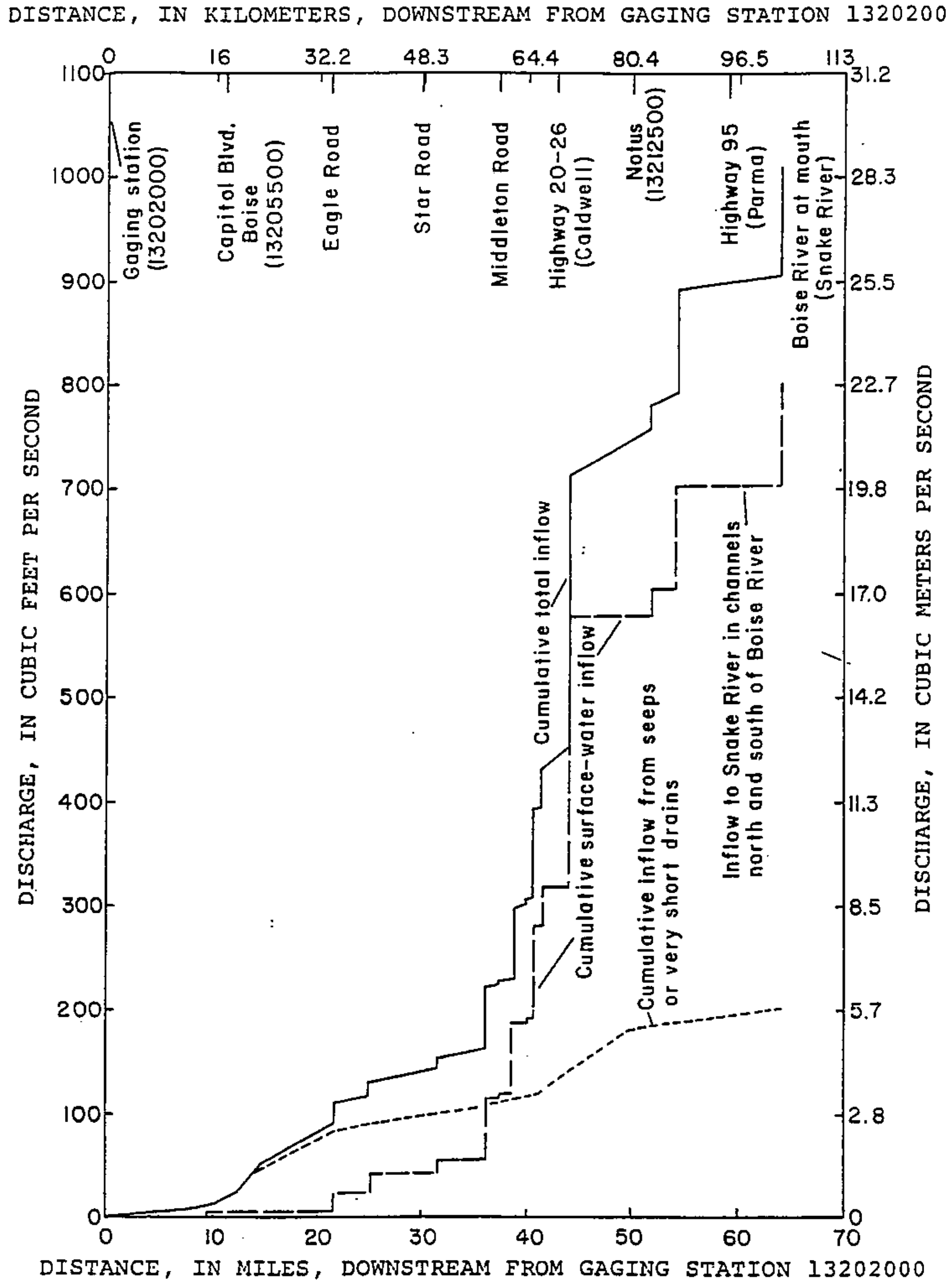


Figure 2. Graph of cumulative inflow to the Boise River between Lucky Peak Dam and mouth November 18-19, 1971 when flow from Lucky Peak Dam was virtually shut off. Lack of inflow above Capital Blvd. suggests that the region between Barber Dam and west Boise is a recharge area, whereby the river is losing water to aquifers. From Thomas and Dion (1972).

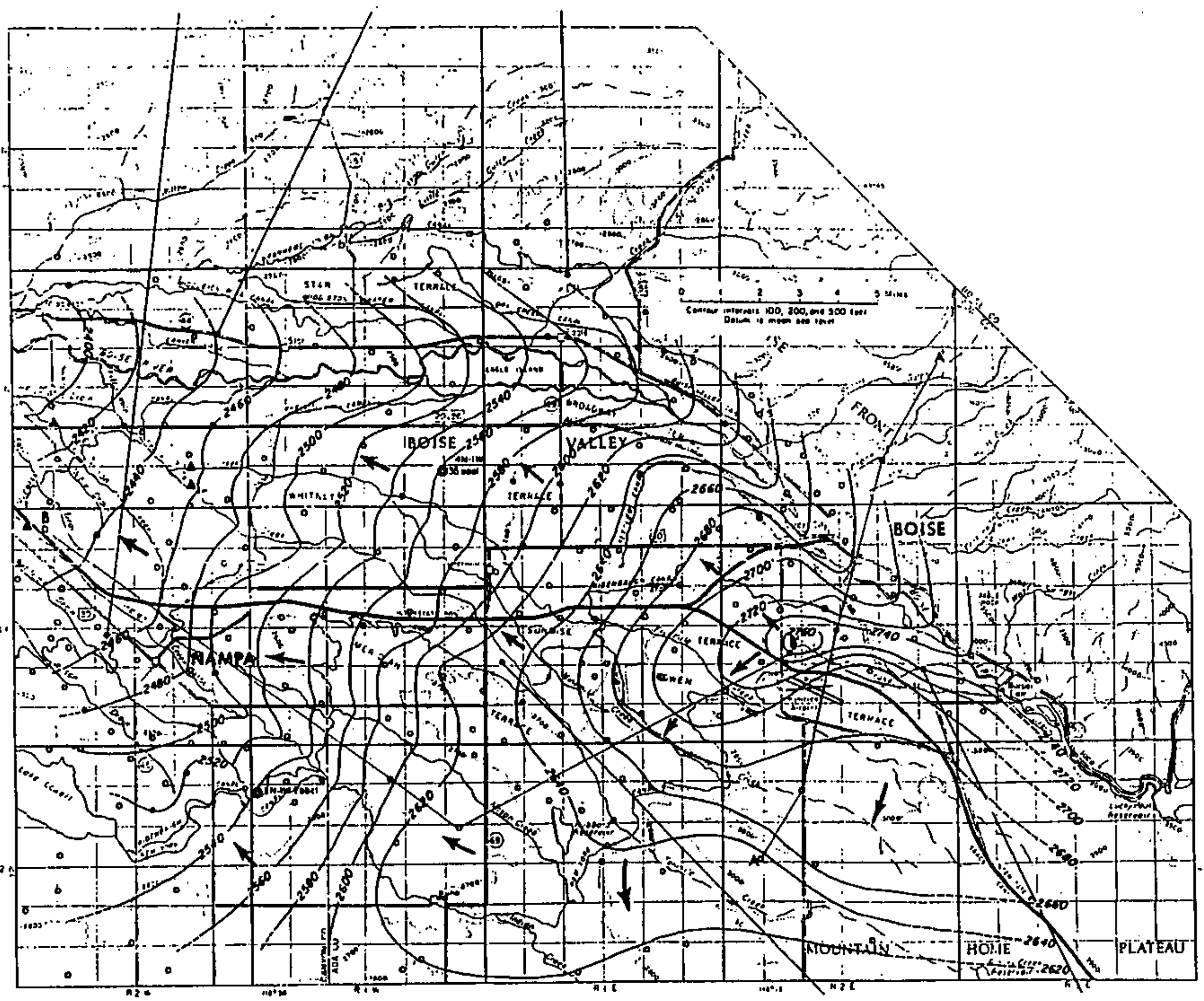
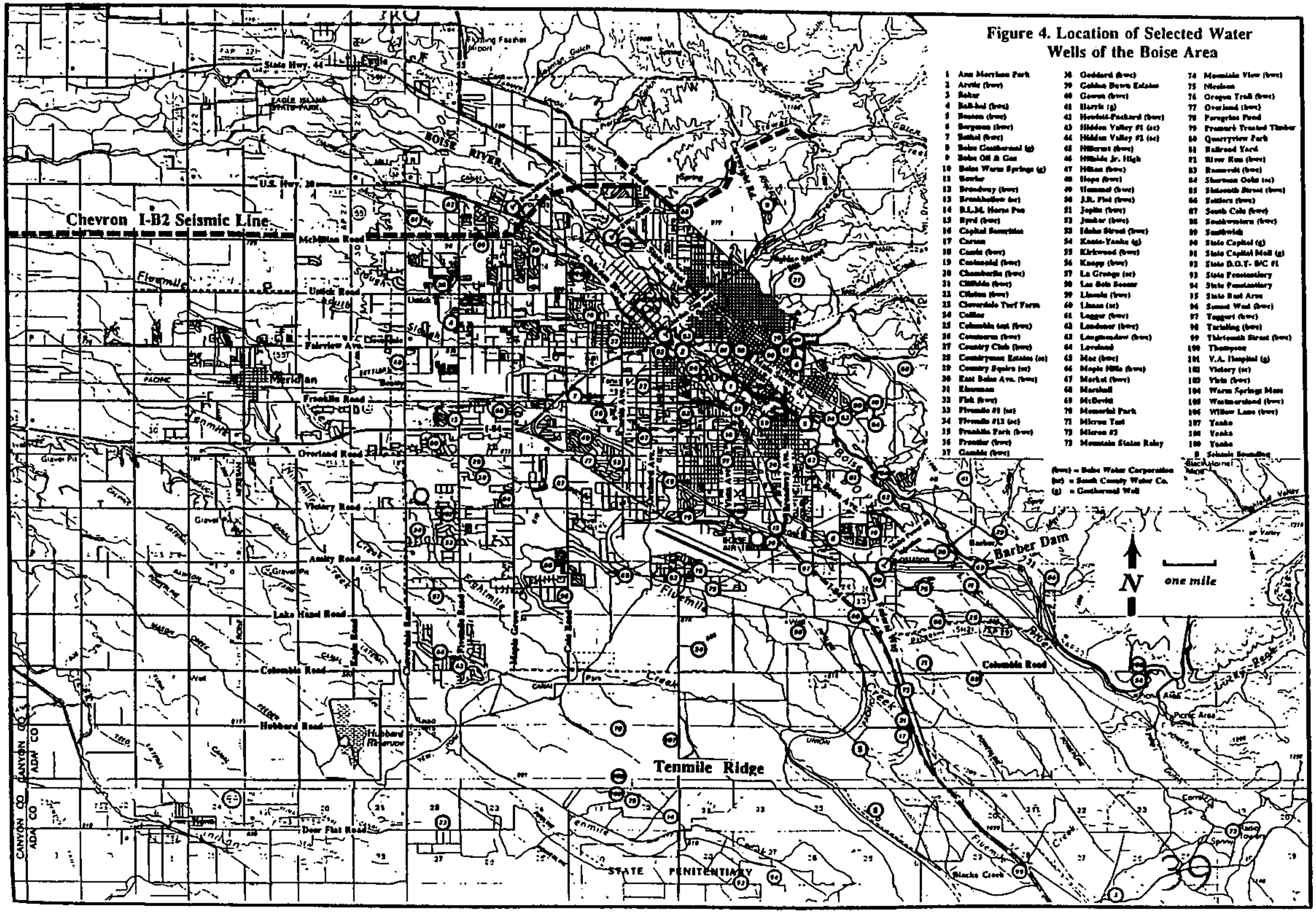


Figure 3. Contour map of the water level in wells, mostly data from shallow wells, Oct., 1972. From Dion (1972).

Figure 4. Location of Selected Water Wells of the Boise Area



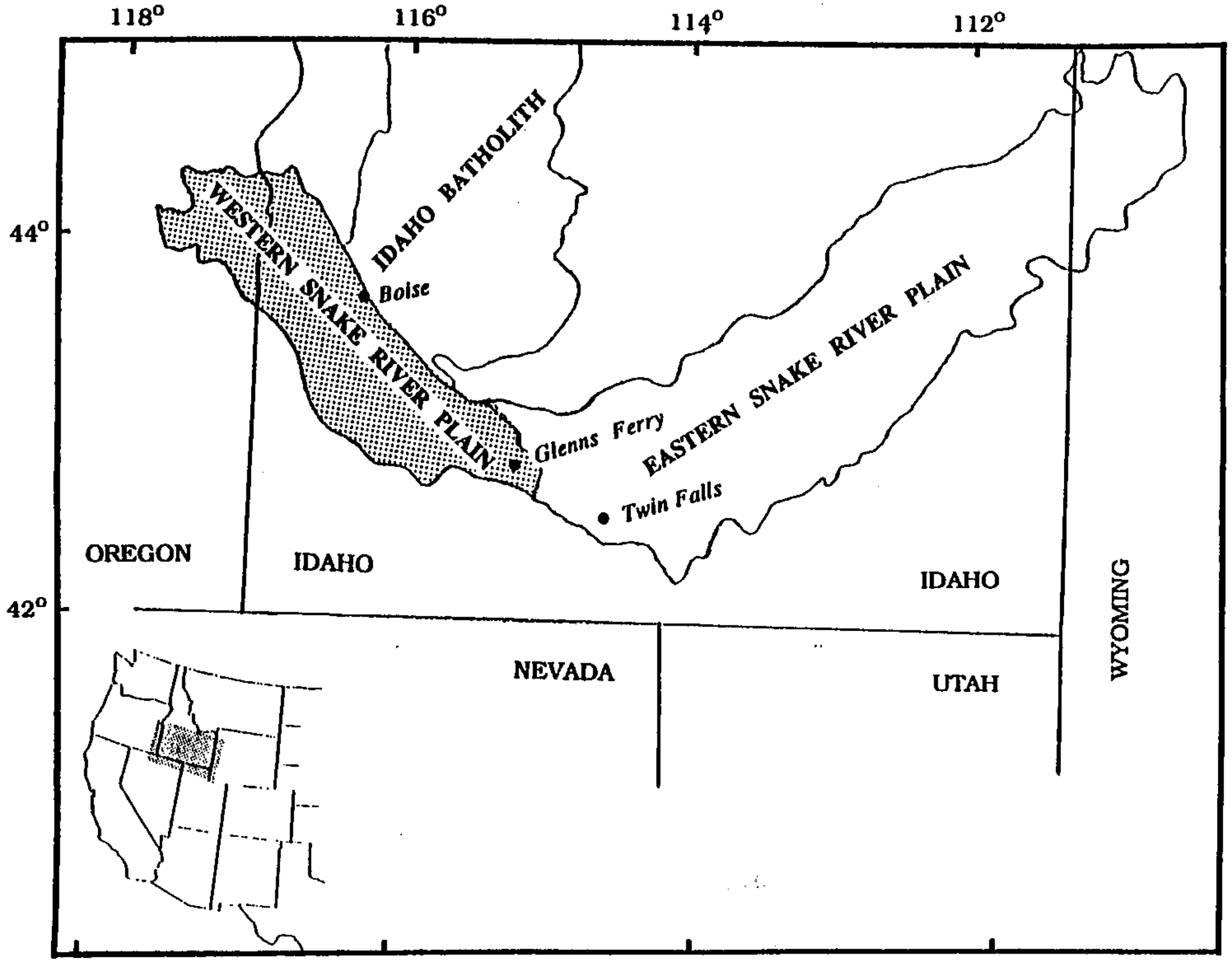


Figure 5. Location and extent of western Snake River Plain.

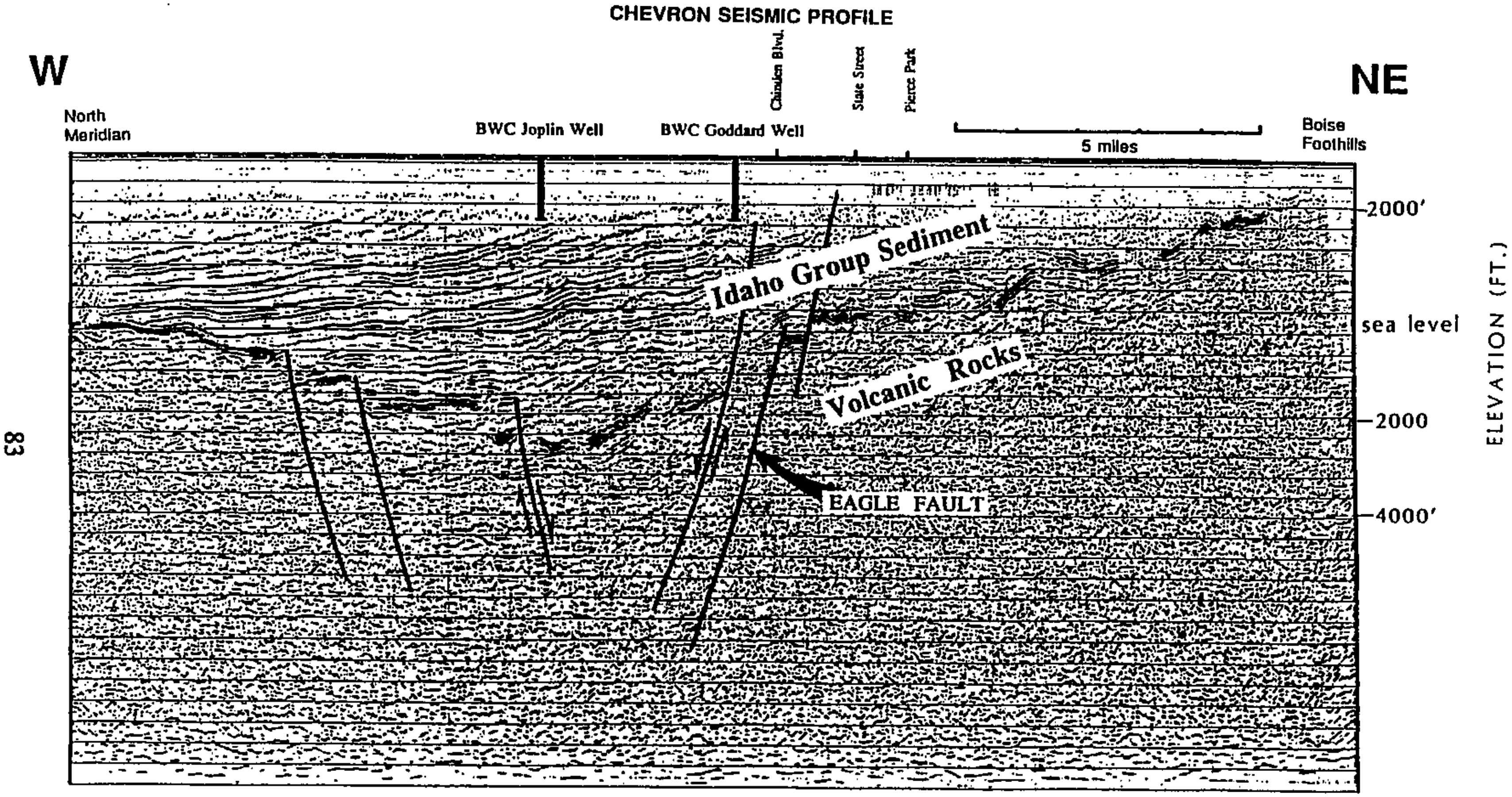


Figure 6. Cross-section view of subsurface layers beneath the Boise River Valley as shown by a seismic reflection profile. Profile extends southwest from Stewart Gulch in the foothills and then westward along McMillan Road to Meridian. Reflections within the Idaho Group sediment are from interfaces between sand and mudstone layers. Shaded reflection is the interface between the sedimentary section and the lower volcanic section of rocks. The section shows layers of Idaho Group sediments dipping southwestward about 4 to 6°, and the major faults offsetting the deeper strata. (original data obtained by Chevron Oil Co., Line IB-2, reprocessed. Reflection data from shallowest 600 ft. was not obtained owing to long source-receiver distance).

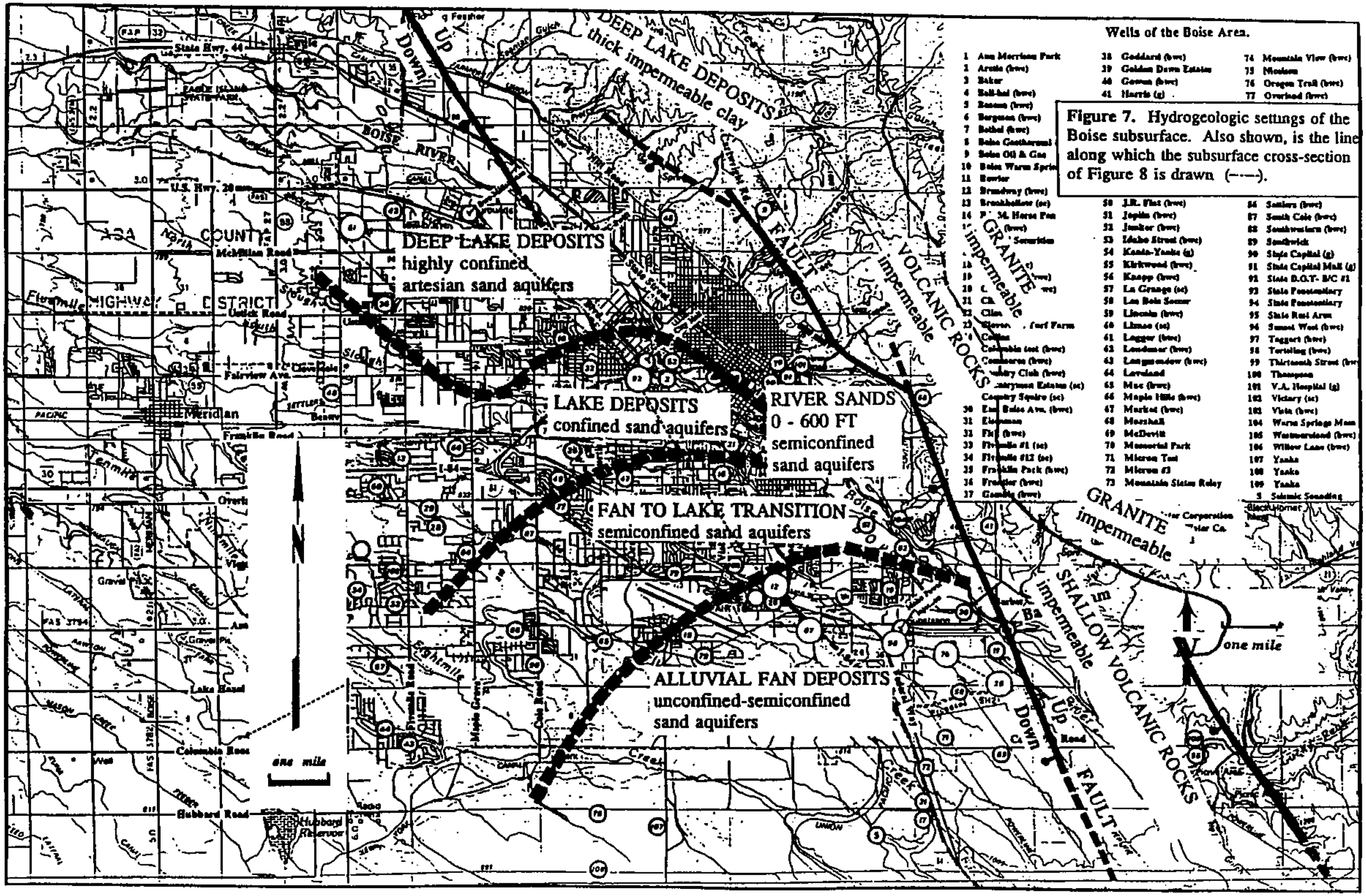


Figure 7. Hydrogeologic settings of the Boise subsurface. Also shown, is the line along which the subsurface cross-section of Figure 8 is drawn (–·–).

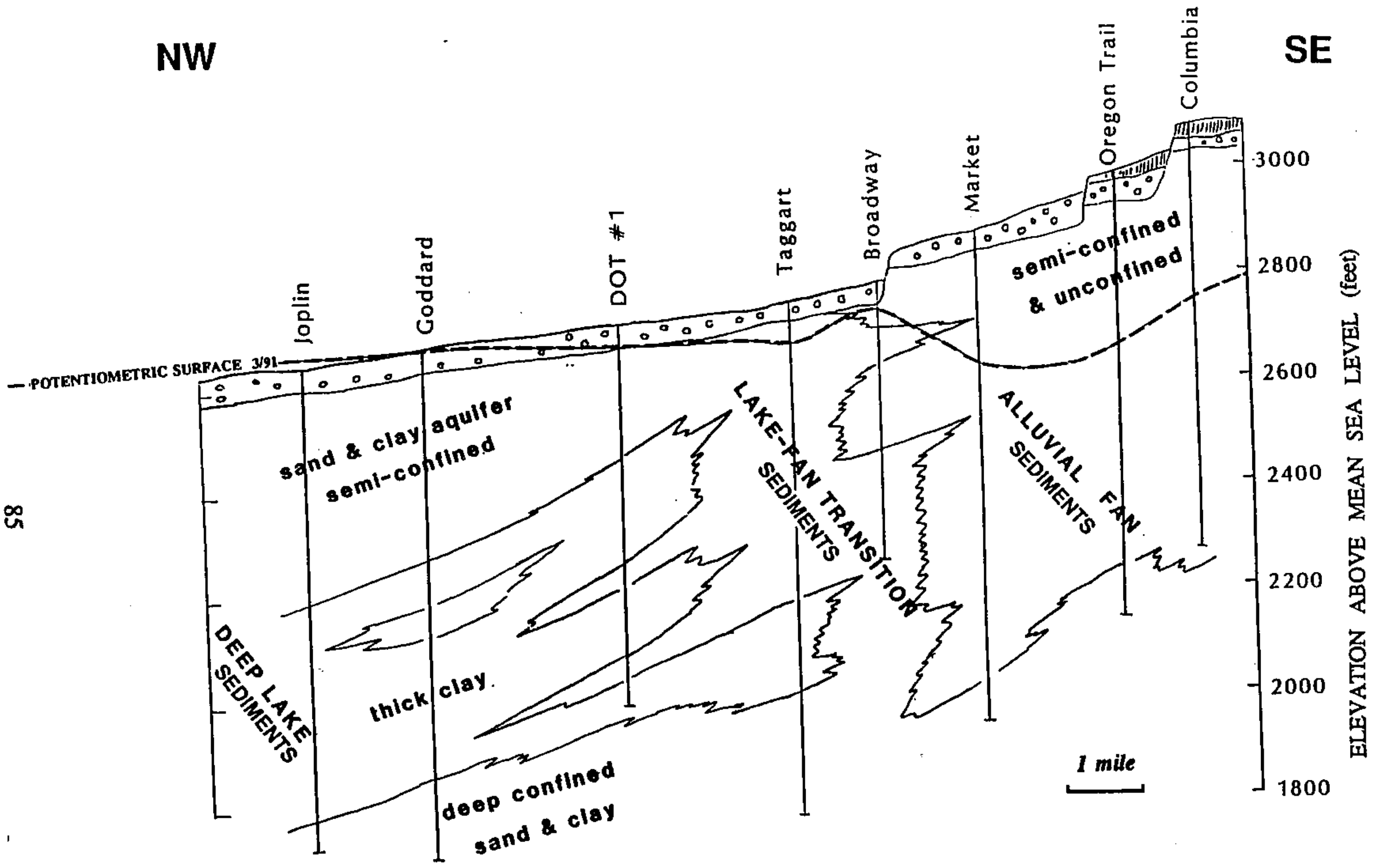


Figure 8. Idealized cross-section showing the sub-surface distribution of hydrogeologic settings of the Boise Valley with representative wells. Line of cross-section and areal (map view) extent of the hydrogeologic settings is shown on Figure 7.

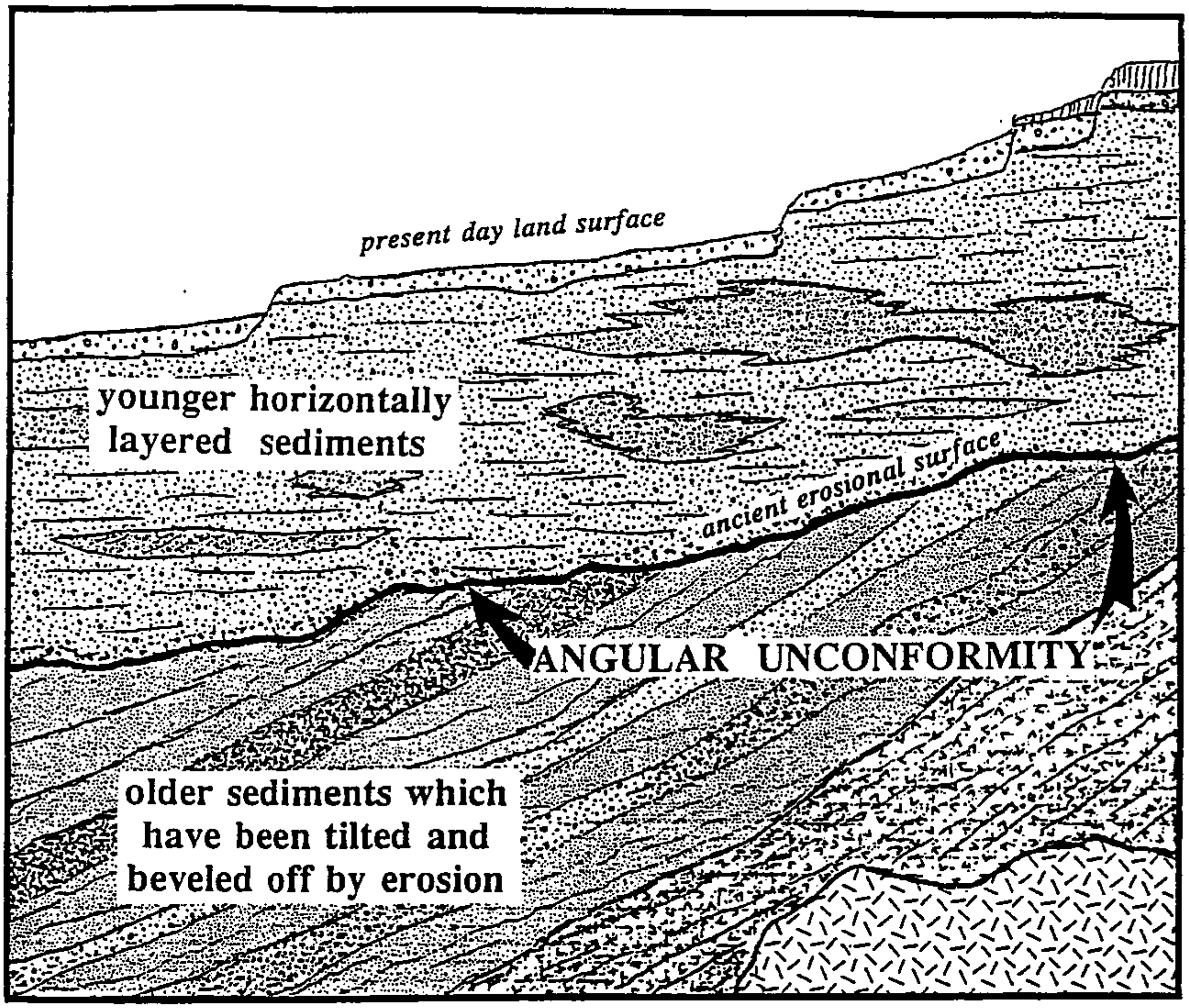


Figure 9. Generalized diagram of the angular unconformity believed to exist in the sub-surface beneath Boise. This structure is present at 400 to 500 feet below land surface where older sedimentary strata of the Idaho Group have been tectonically tilted 4° to 7° in response to extentional faulting and downwarping of the western Snake River Plain. After erosional processes beveled off the tilted layers, deposition resumed with the accumulation of nearly horizontal strata over the erosional surface.

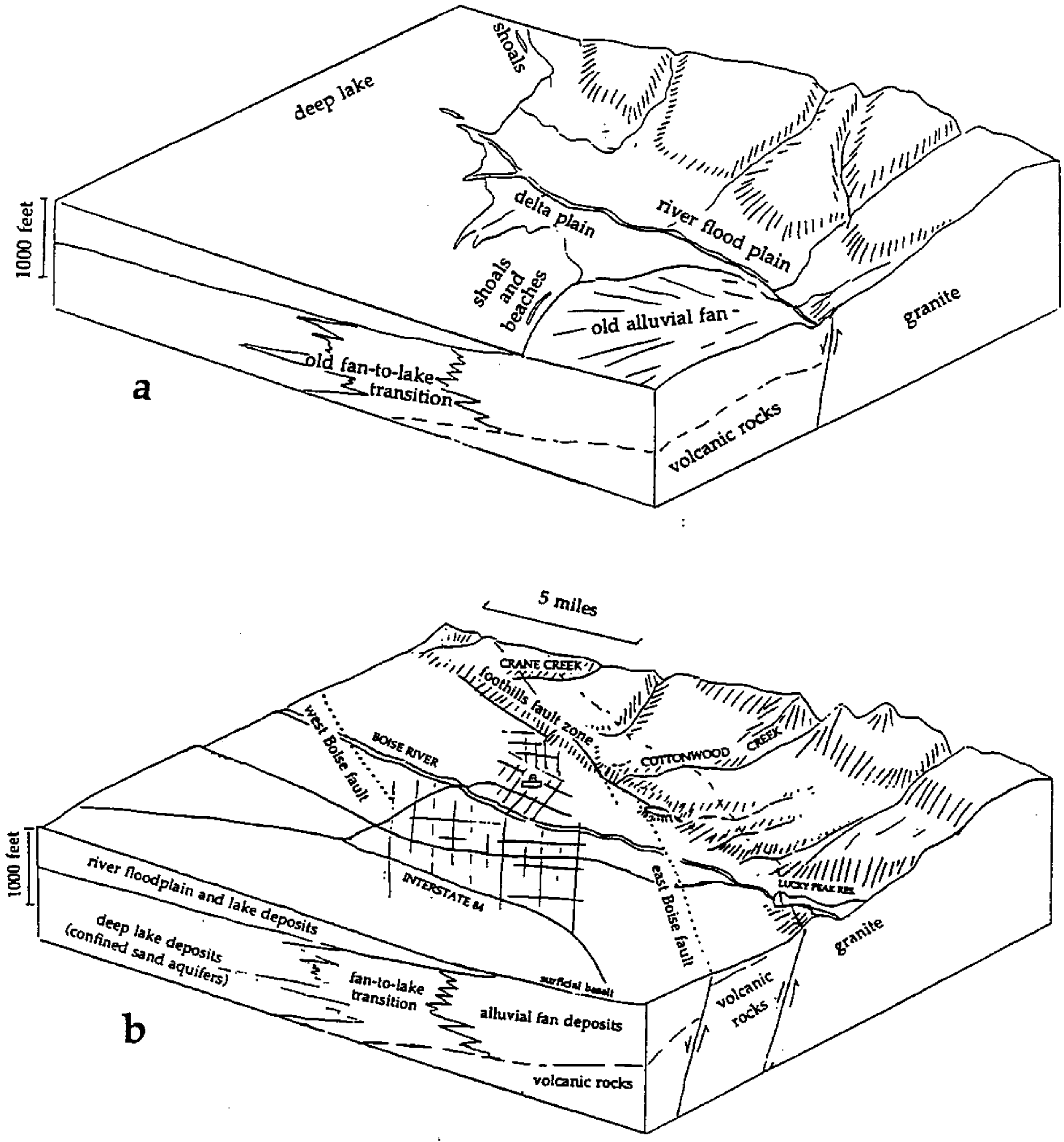


Figure 10. (a) An illustration of the depositional environment hypothesized for the upper part of the aquifer system beneath Boise Valley. Illustration shows Lake Idaho indundating the lower foothills and older alluvial fans. A major river flows along the base of the foothills spreading deltaic sediments into the lake. (b) Geologic framework for the aquifer system beneath the Boise Valley as it is today (the illustration summarizes many of the new findings of the present study).

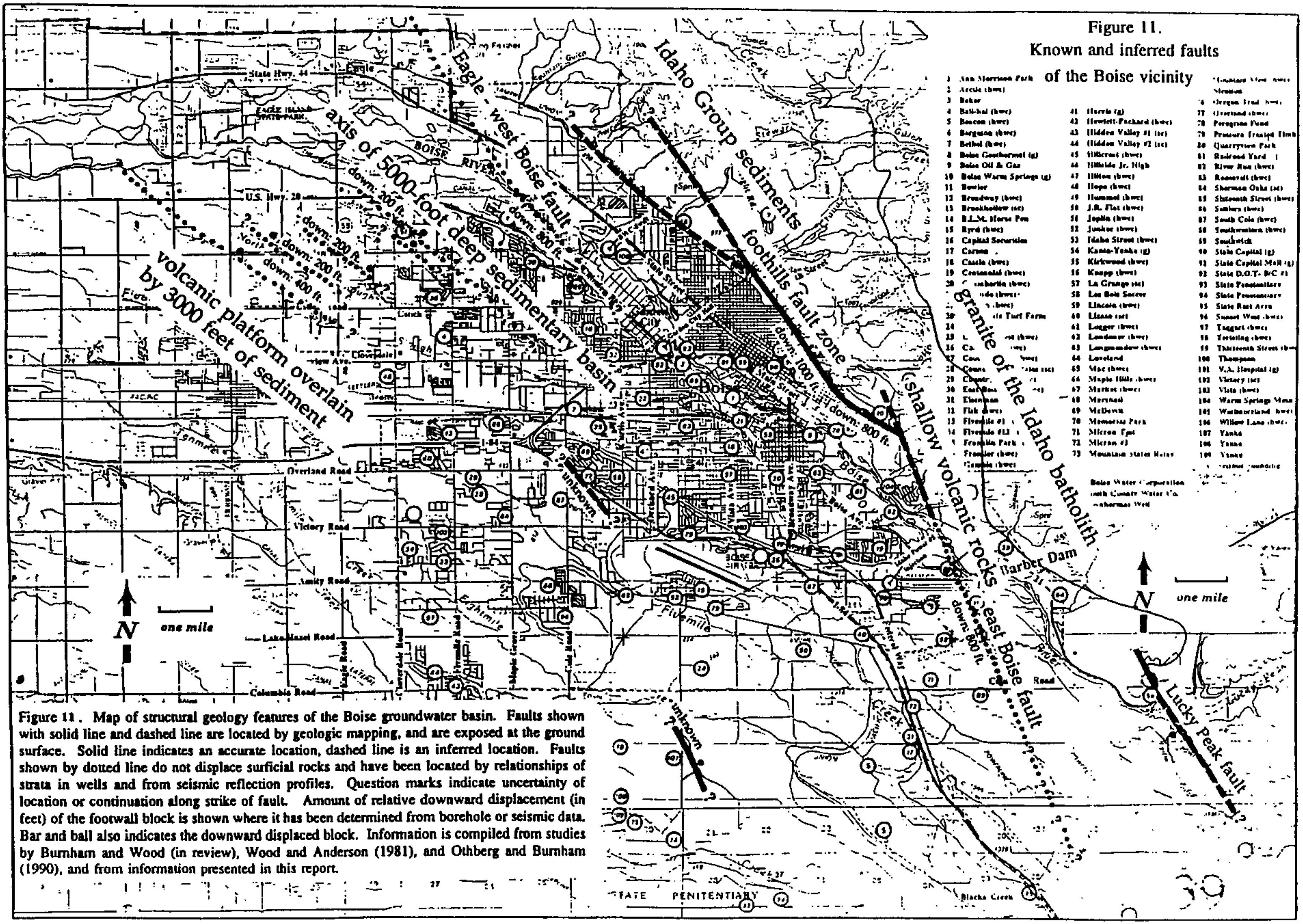


Figure 11. Map of structural geology features of the Boise groundwater basin. Faults shown with solid line and dashed line are located by geologic mapping, and are exposed at the ground surface. Solid line indicates an accurate location, dashed line is an inferred location. Faults shown by dotted line do not displace surficial rocks and have been located by relationships of strata in wells and from seismic reflection profiles. Question marks indicate uncertainty of location or continuation along strike of fault. Amount of relative downward displacement (in feet) of the footwall block is shown where it has been determined from borehole or seismic data. Bar and ball also indicates the downward displaced block. Information is compiled from studies by Burnham and Wood (in review), Wood and Anderson (1981), and Othberg and Burnham (1990), and from information presented in this report.

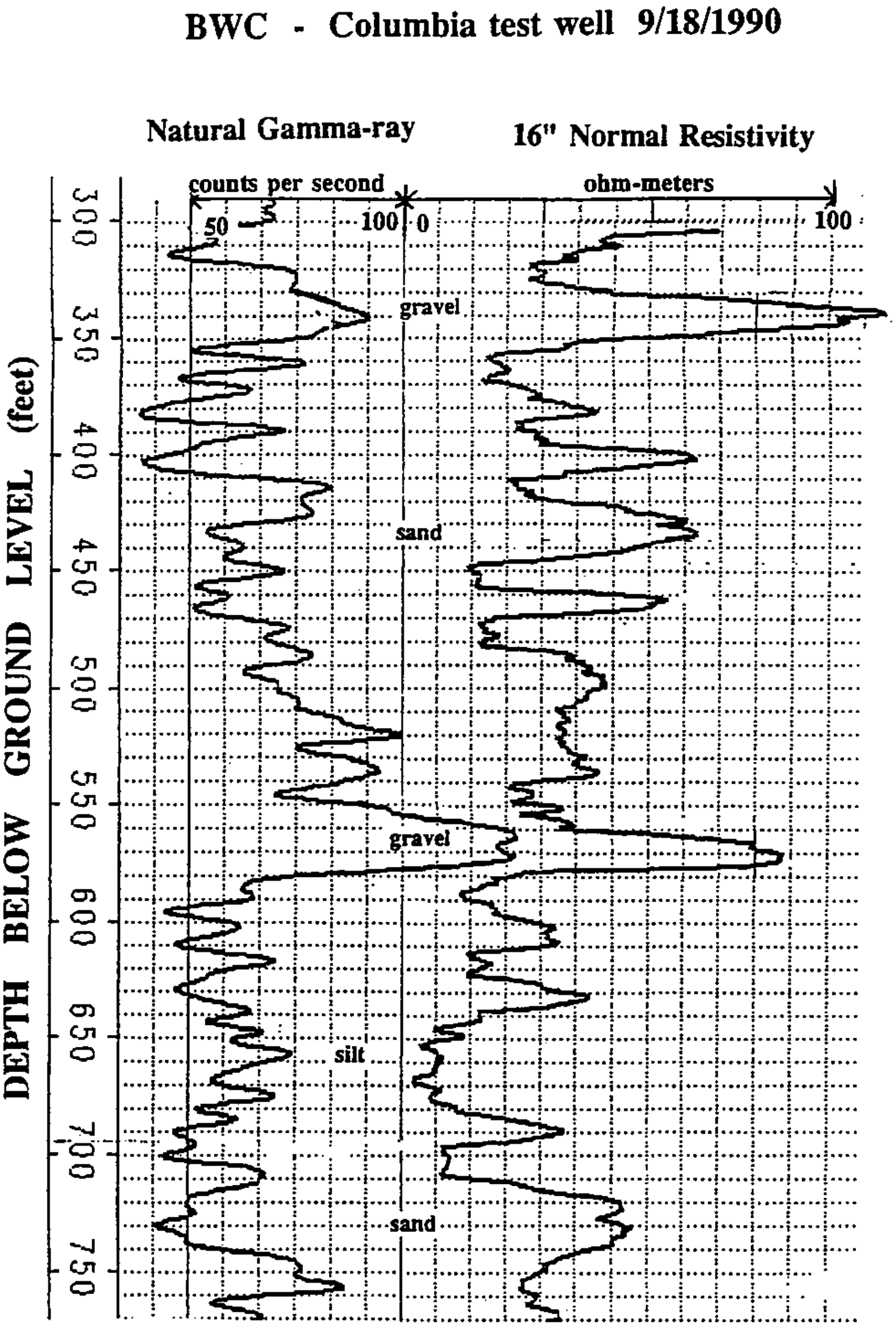


Figure 12. Geophysical log character of the Boise alluvial-fan. The complex interbedded nature of thin gravel, sand, and silt units is shown by the apparent erratic and "spiky" natural gamma-ray and 16" normal resistivity log response to the BWC Columbia test well 9/18/90. Gravels are indicated by high gamma-ray and high resistivity response. Sands also show high resistivity but have lower gamma-ray activity. Silts and silty clays are characterized by low resistivity values but moderate gamma-ray counts. Location of the Columbia test well is shown on Fig. 4.

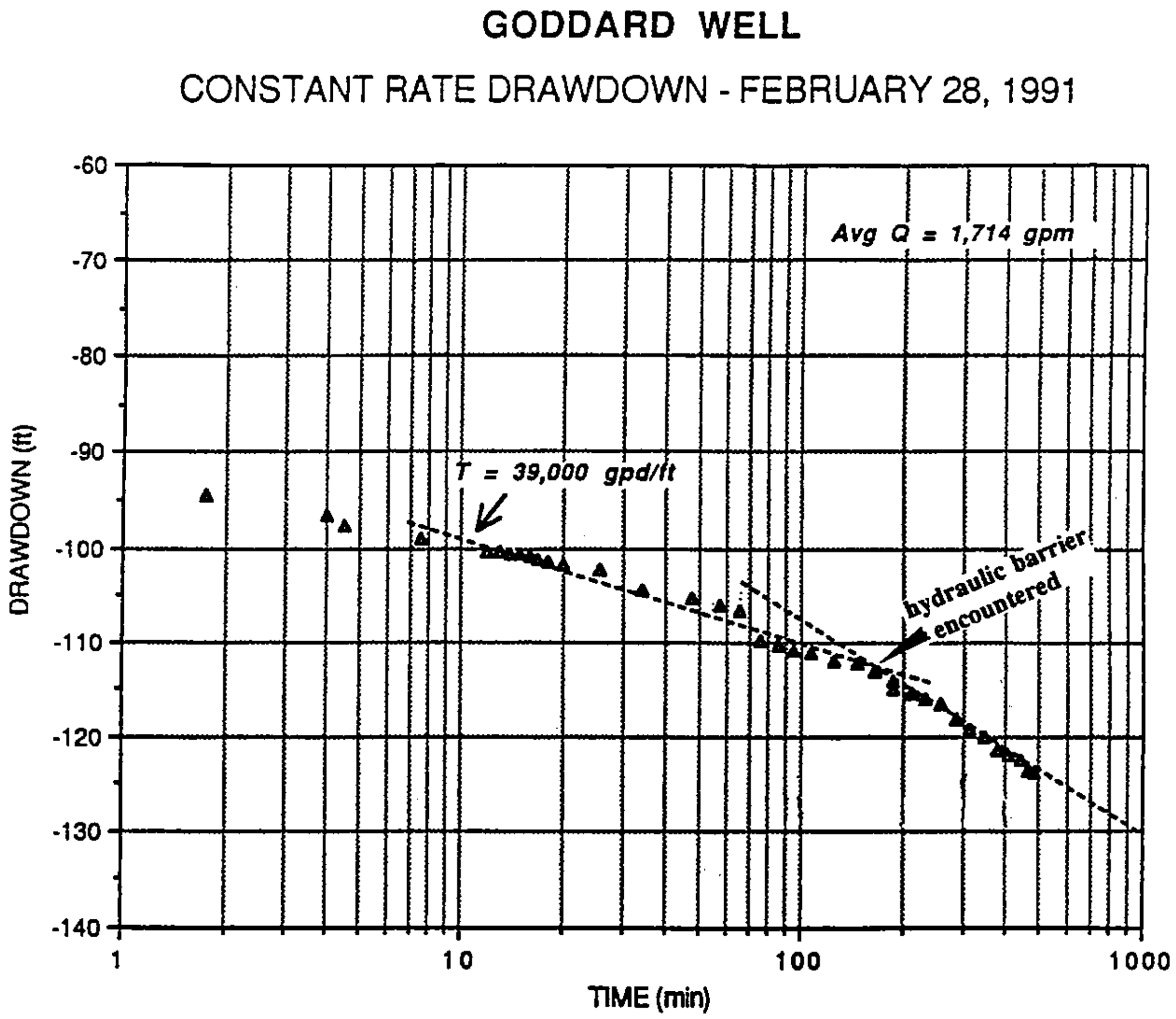


Figure 13. Semi-log plot of drawdown versus time for the performance/completion test of the BWC Goddard Street #2 production well (after Mills, 1991). Approximately 180 minutes into the test, the water-level in the well began to lower at an increasing rate indicating that a negative hydraulic barrier had been encountered by the pumped-well cone of depression. Such barriers may be in the form of any of the following: 1) natural depositional thinning of the aquifer (reduced transmissivity), 2) erosional truncation of the aquifer updip; either at the surface or at depth along an angular unconformity, 3) truncation of the aquifer by faulting, whereby permeable aquifer materials may be juxtaposed against less permeable or cemented strata, 4) decreased aquifer permeability at some distance from the well due to lateral changes in sediment type, or 5) the pumping-well cone of depression encountering the cone of depression of an adjacent pumping-well (well interference).

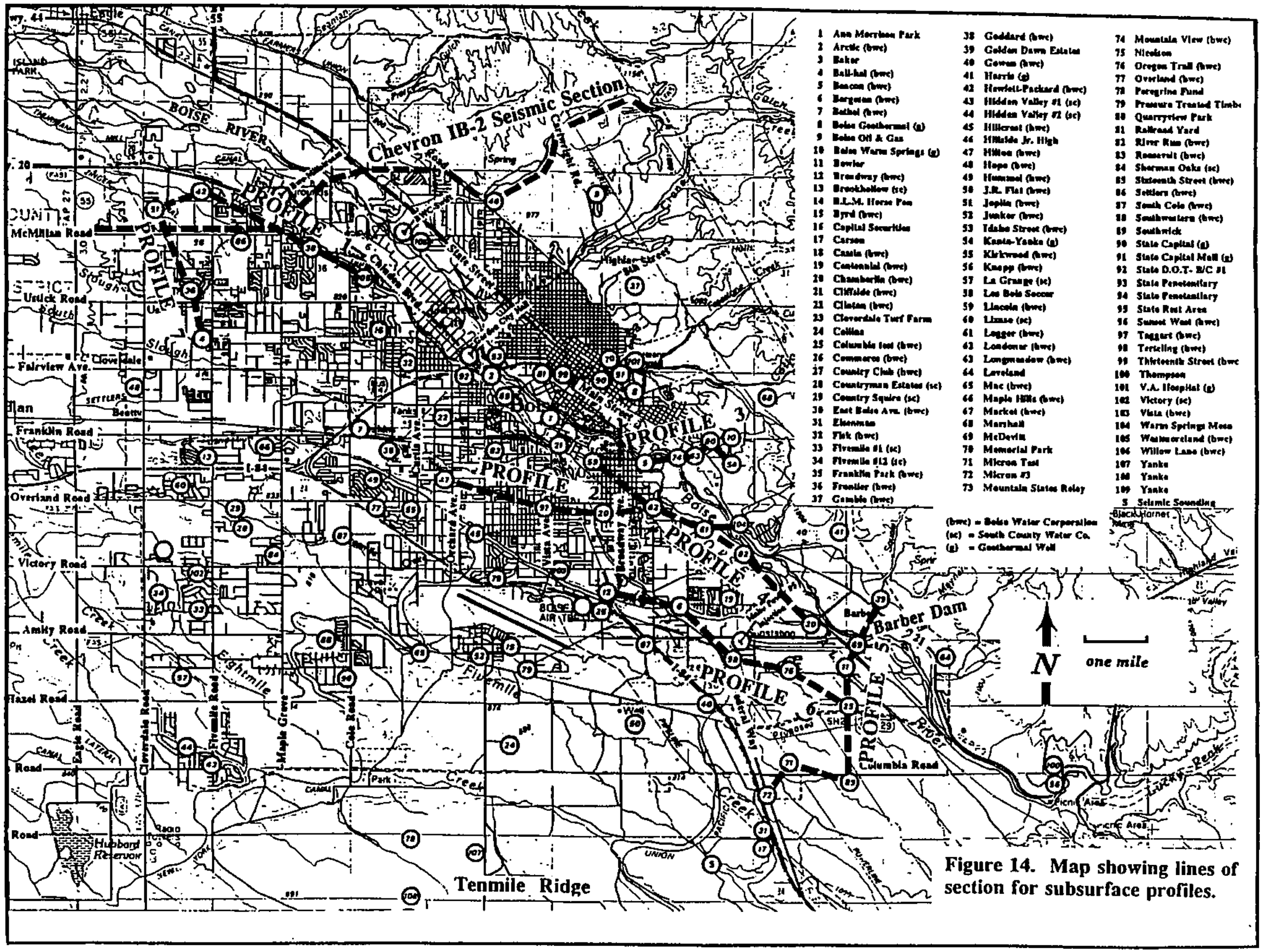


Figure 14. Map showing lines of section for subsurface profiles.

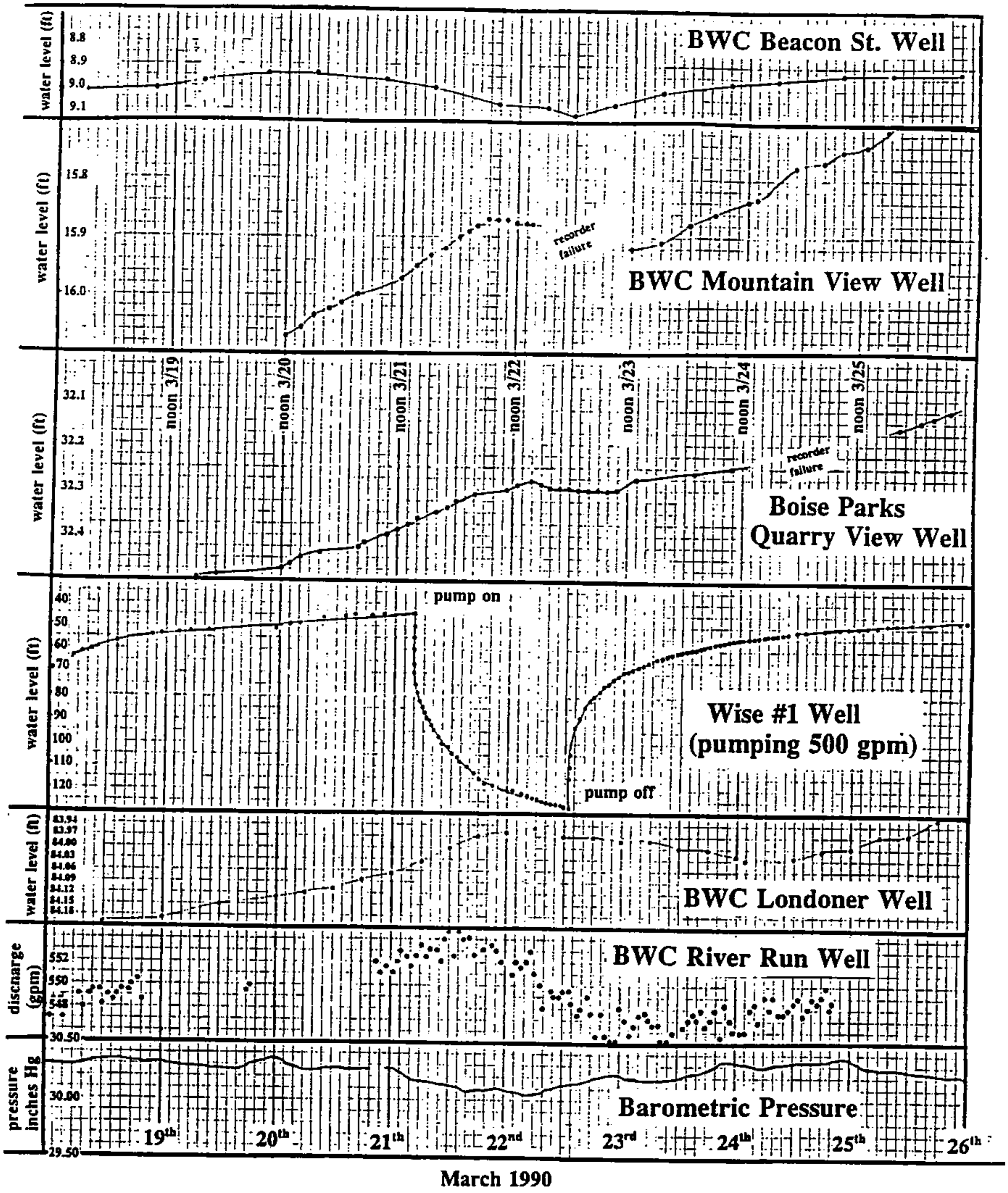
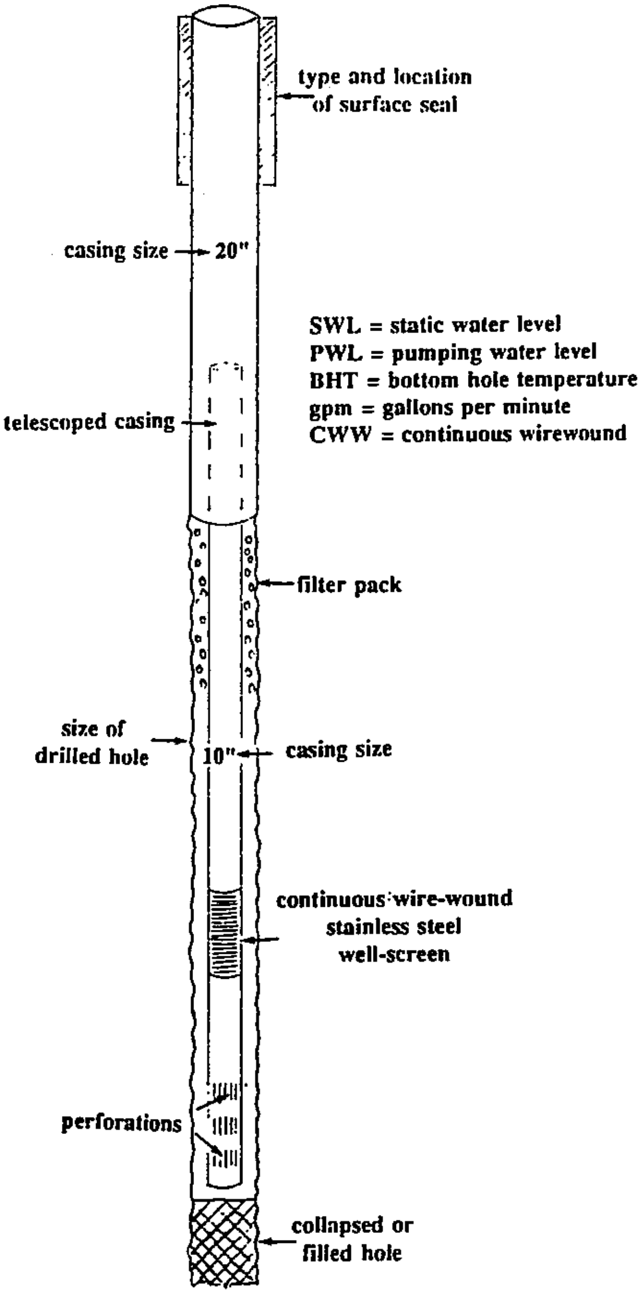


Figure 15. March 1990 testing of the Mesa Water Corporation (MWC) #1 production well. The MWC #1 well was allowed to recover before being pumped at an average rate of 474 gpm for about 30 hours. Measurements were taken in the pumping well using an electric wireline well sounder. The Boise Water Corporation's (BWC) Beacon Street, Londoner test, and Mountain View wells and the Boise Parks Department's Quarry View well were instrumented with Stevens F-type recorders to monitor water-levels during the test. The BWC River Run production well was monitored using the BWC telemetry system. The River Run well is equipped with a special pump which is designed to maintain a constant head above the pump bowls. For this reason, the discharge of the well was monitored instead of water-level. It was anticipated that any water-level decline in the River Run well in response to pumping the MWC #1 well would cause a decrease in the discharge of the River Run well as the pump adjusted its discharge to maintain a constant water-level in the well. Water levels in all the wells were rising steadily before the test, presumably recovering from the previous pumping season, but these recovery trends were interrupted and reversed in response to MWC #1 pumping. After the MWC well was turned off the water-levels in the outlying observation wells again resumed the pretest recovery trends. For well locations and well-completion information refer to Figure 4 and Profiles 2 & 3 respectively.

WELL CONSTRUCTION

Well Name
Well Owner
Date Completed
Total Depth



pumping-test data
amount & type of openings
filter pack material
intended use
Driller
drilling method

LITHOLOGY

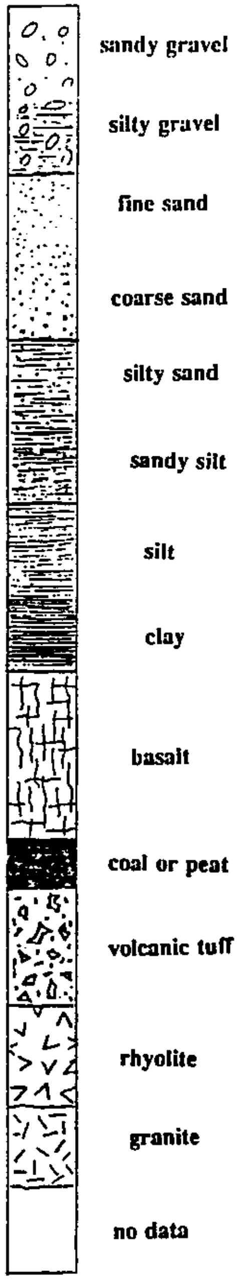
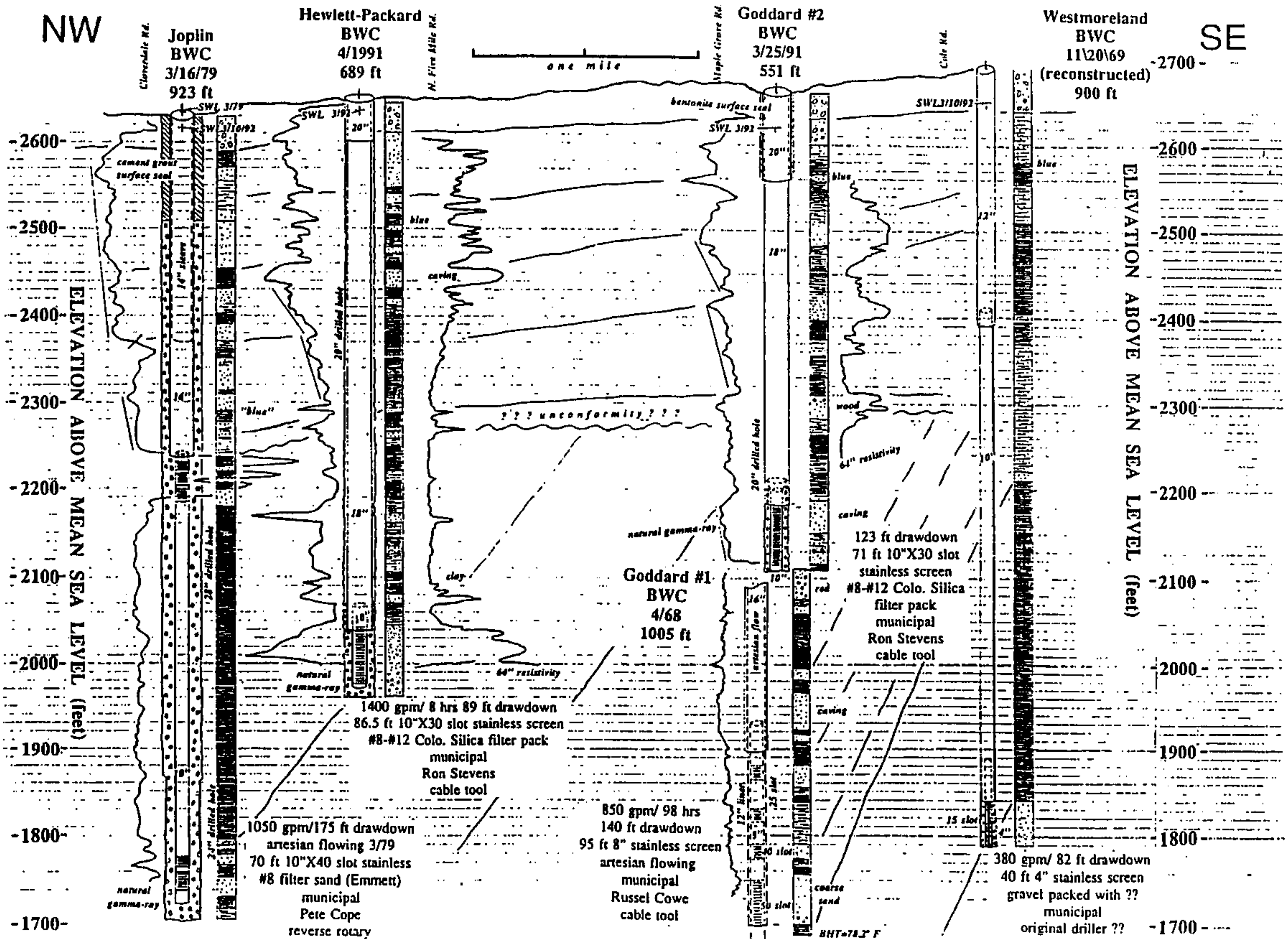
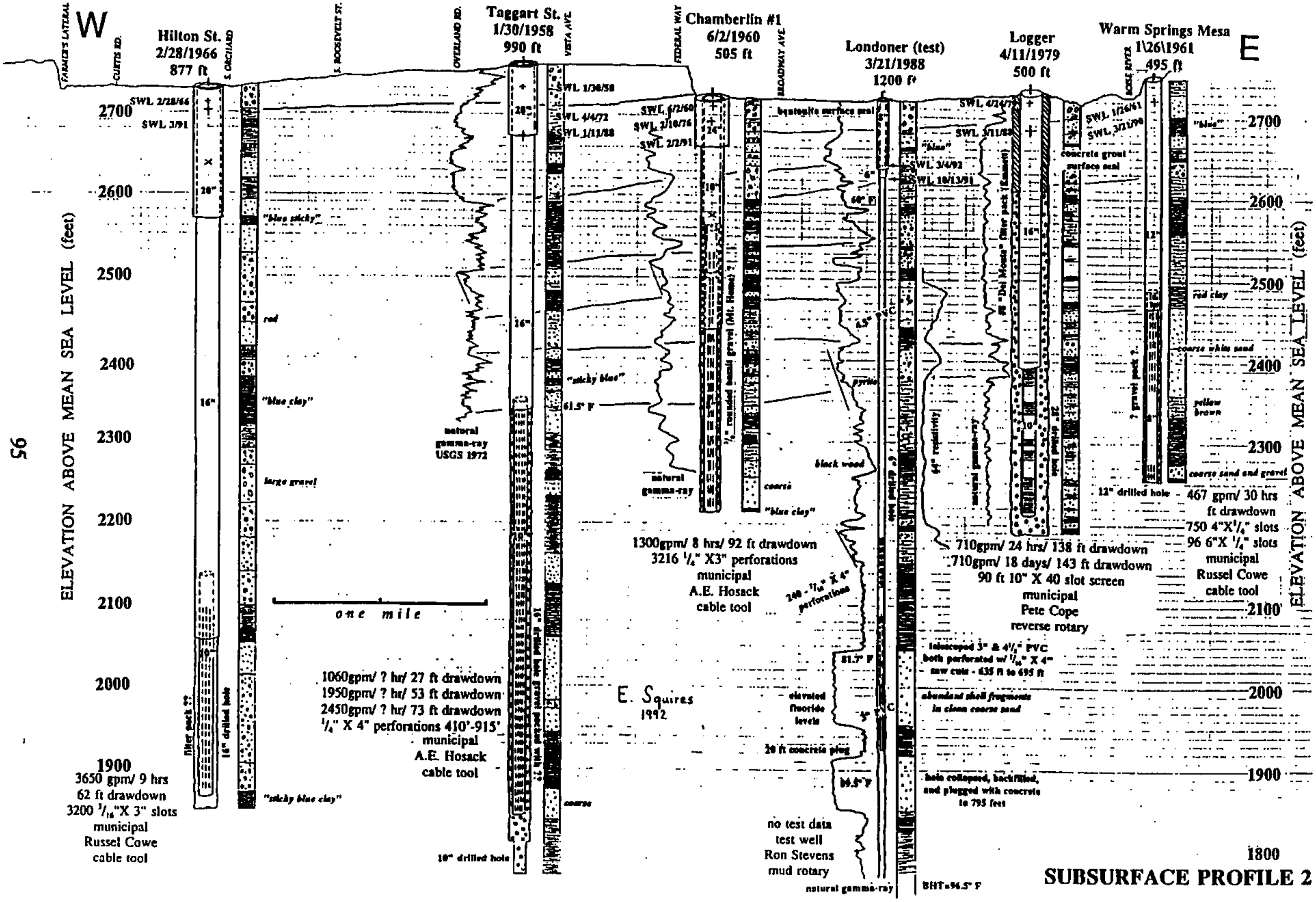


Figure 15. Key to symbols for subsurface profiles.



SUBSURFACE PROFILE 1



3650 gpm/ 9 hrs
62 ft drawdown
3200 1/16"X 3" slots
municipal
Russel Cowe
cable tool

1060gpm/ ? hr/ 27 ft drawdown
1950gpm/ ? hr/ 53 ft drawdown
2450gpm/ ? hr/ 73 ft drawdown
1/4" X 4" perforations 410'-915'
municipal
A.E. Hosack
cable tool

1300gpm/ 8 hrs/ 92 ft drawdown
3216 1/4" X3" perforations
municipal
A.E. Hosack
cable tool

no test data
test well
Ron Stevens
mud rotary

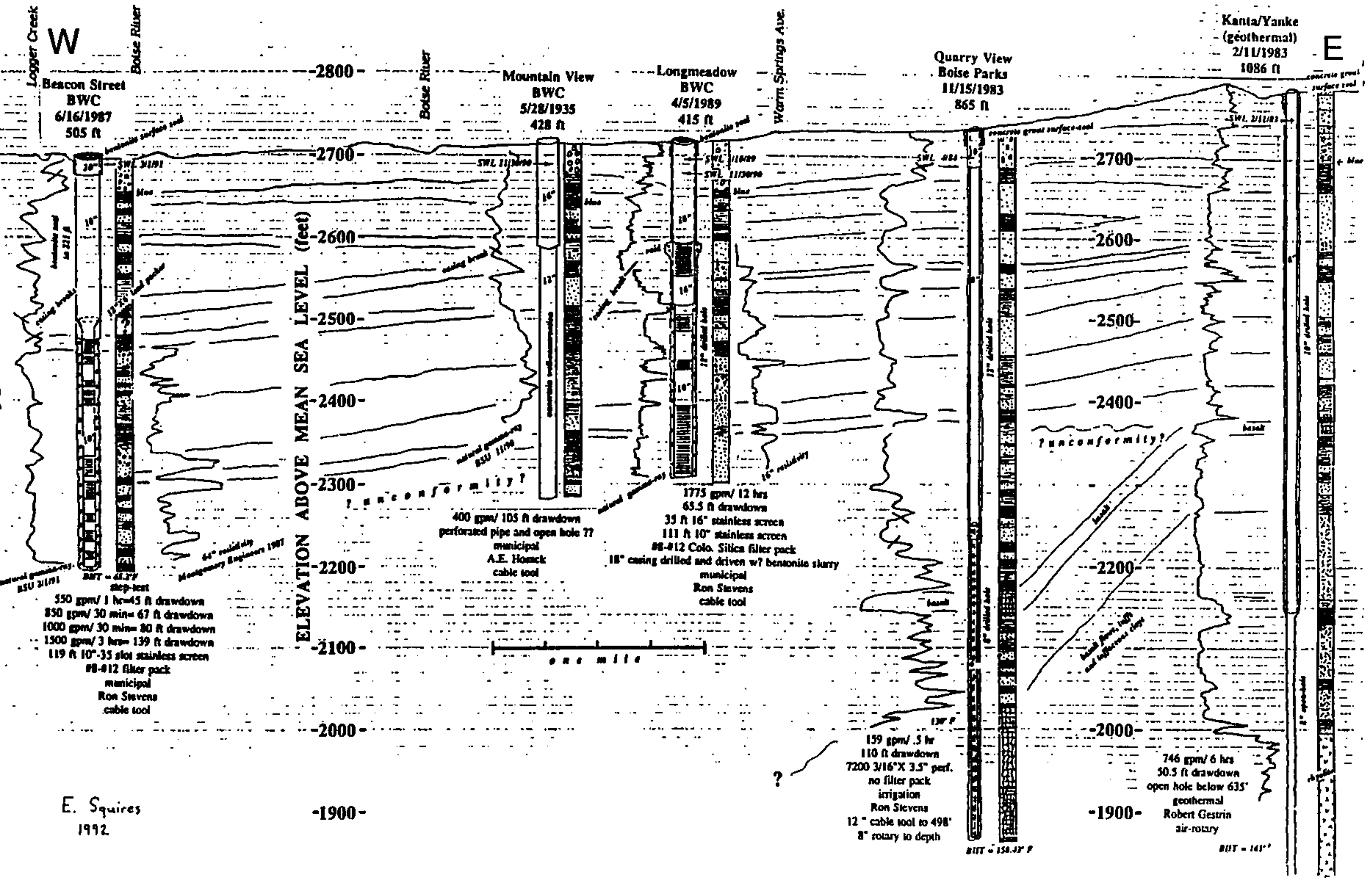
710gpm/ 24 hrs/ 138 ft drawdown
710gpm/ 18 days/ 143 ft drawdown
90 ft 10" X 40 slot screen
municipal
Pete Cope
reverse rotary

467 gpm/ 30 hrs
ft drawdown
750 4"X1/4" slots
96 6"X 1/4" slots
municipal
Russel Cowe
cable tool

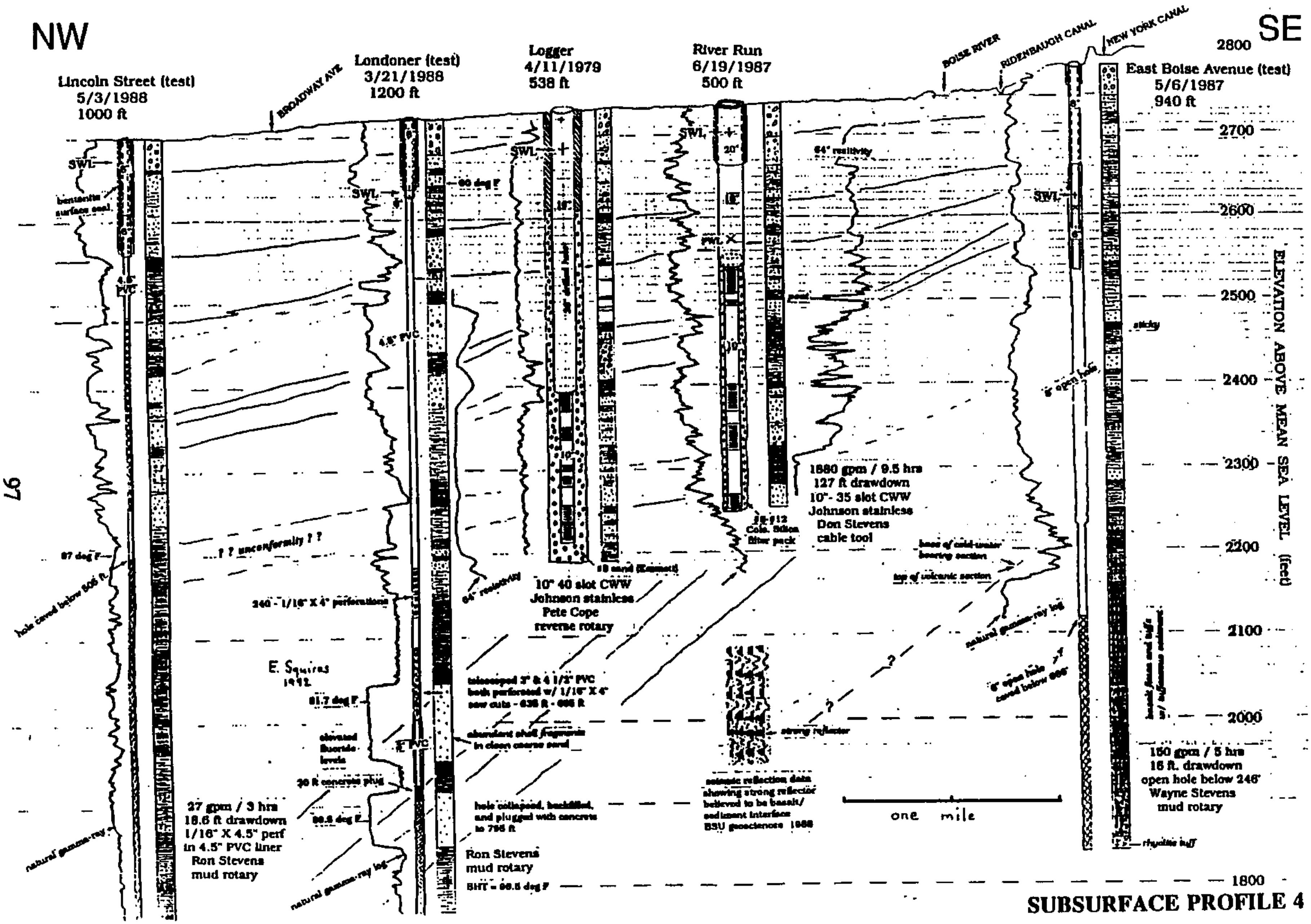
E. Squires
1992

SUBSURFACE PROFILE 2

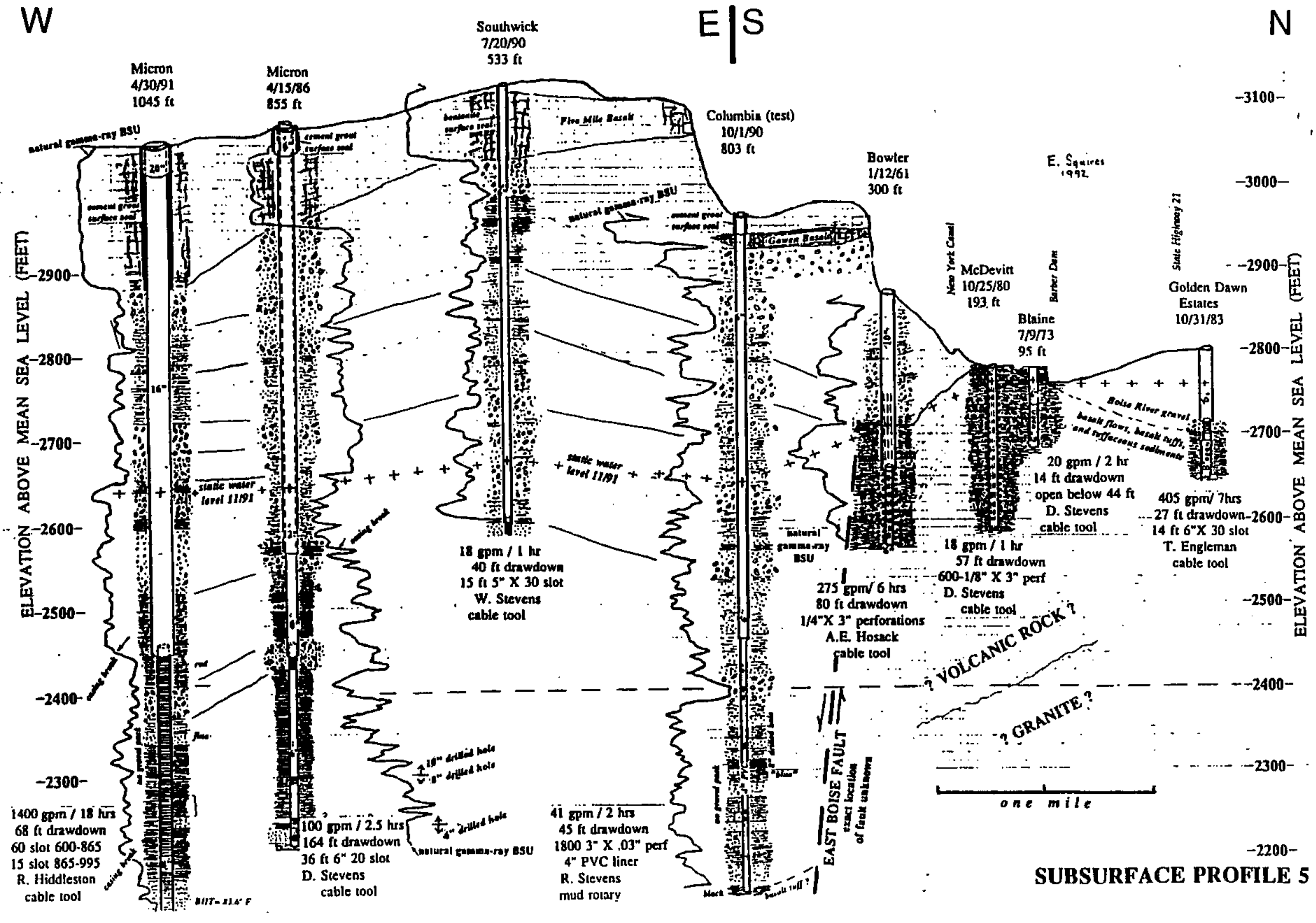
SUBSURFACE PROFILE 3



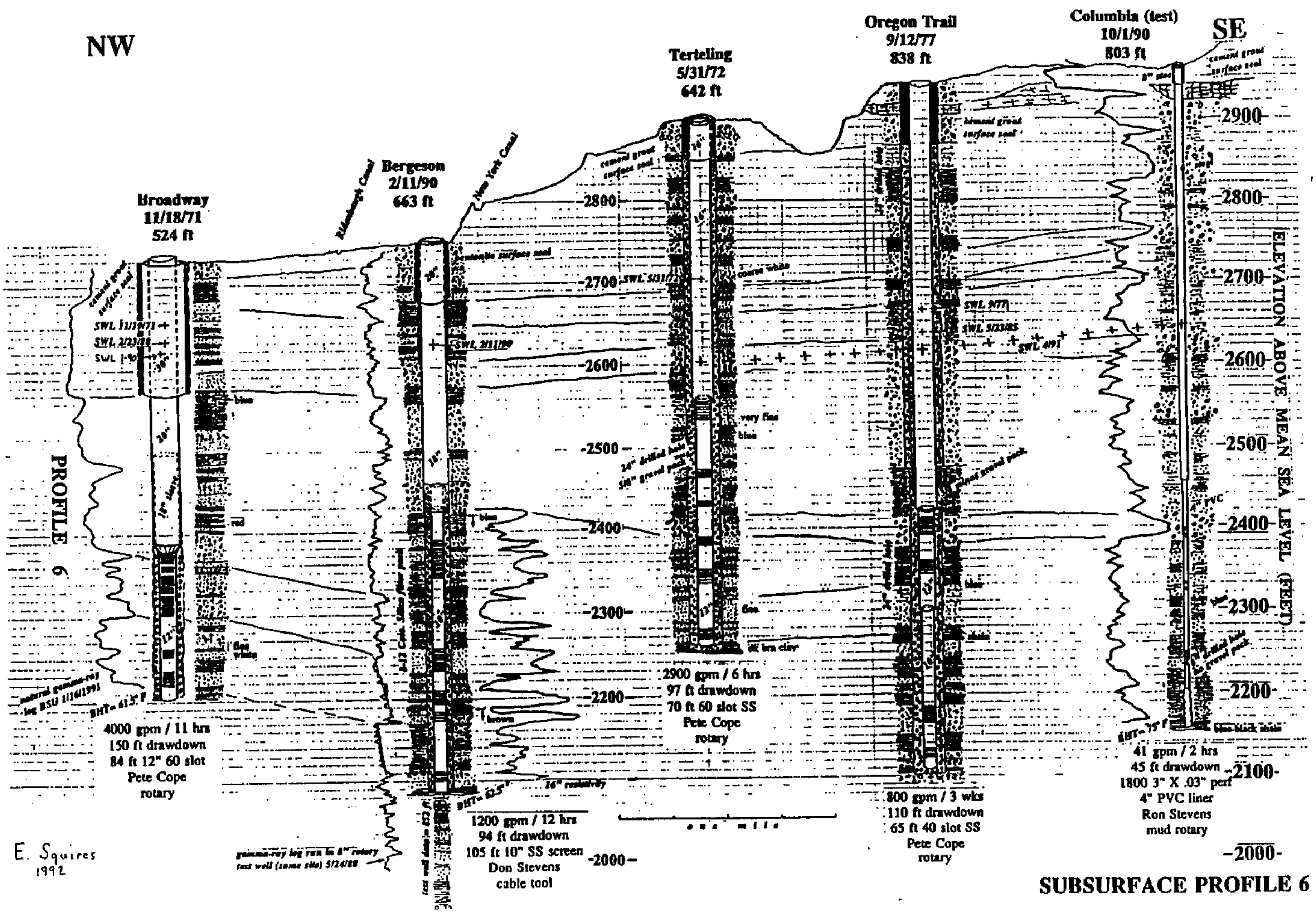
E. Squires
1992



SUBSURFACE PROFILE 4



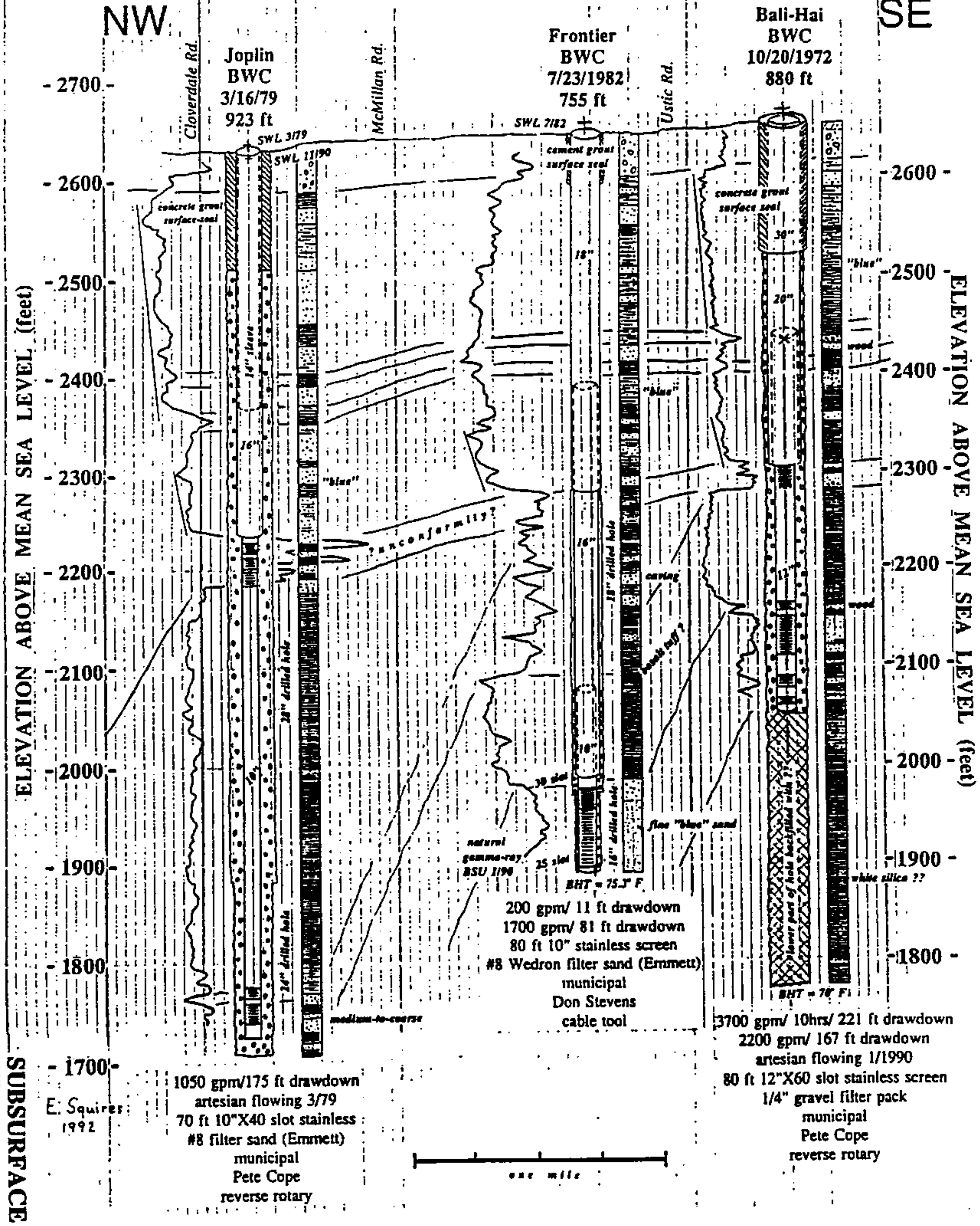
SUBSURFACE PROFILE 5



SUBSURFACE PROFILE 6

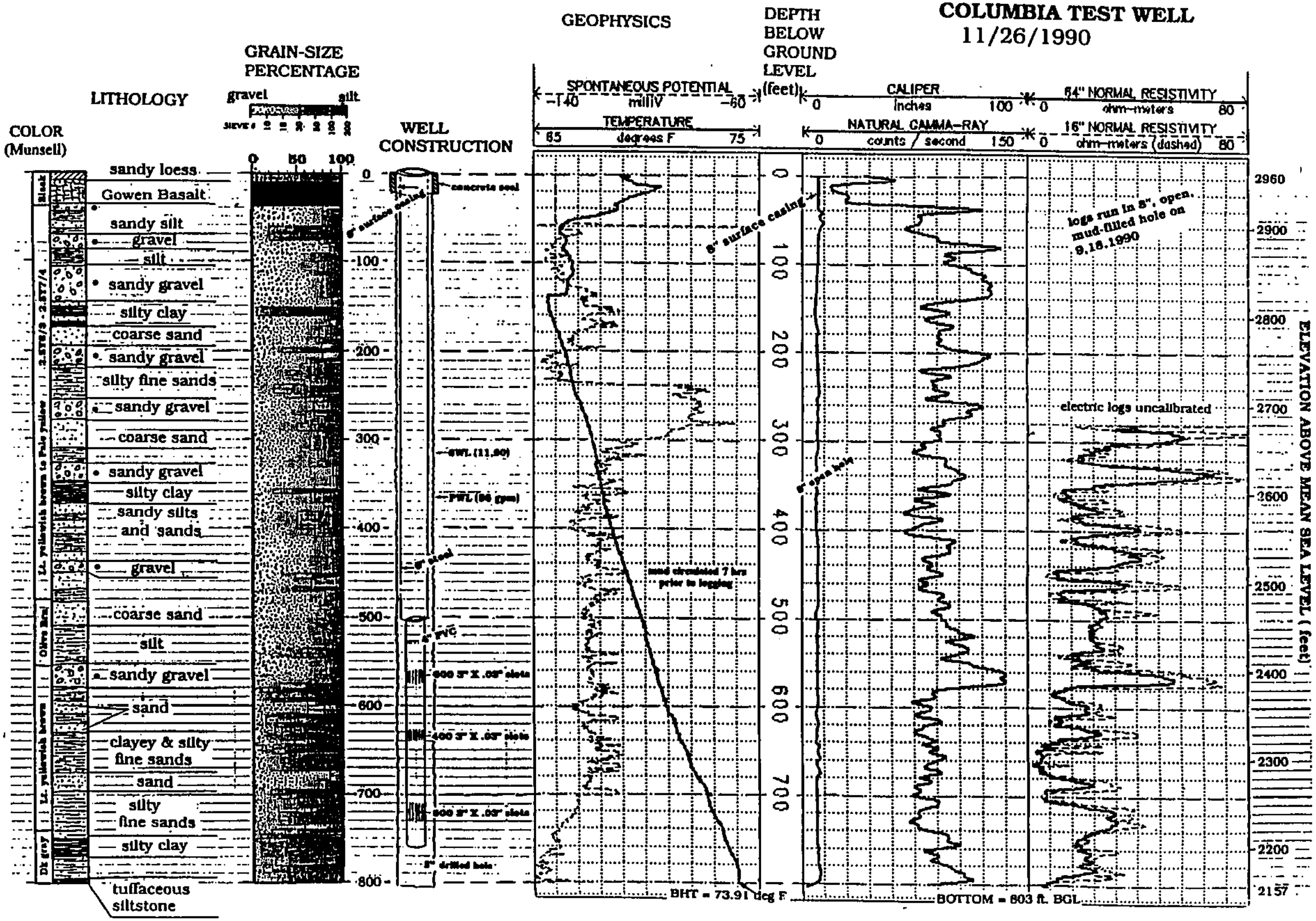
E. Squires
1992

SUBSURFACE PROFILE 7

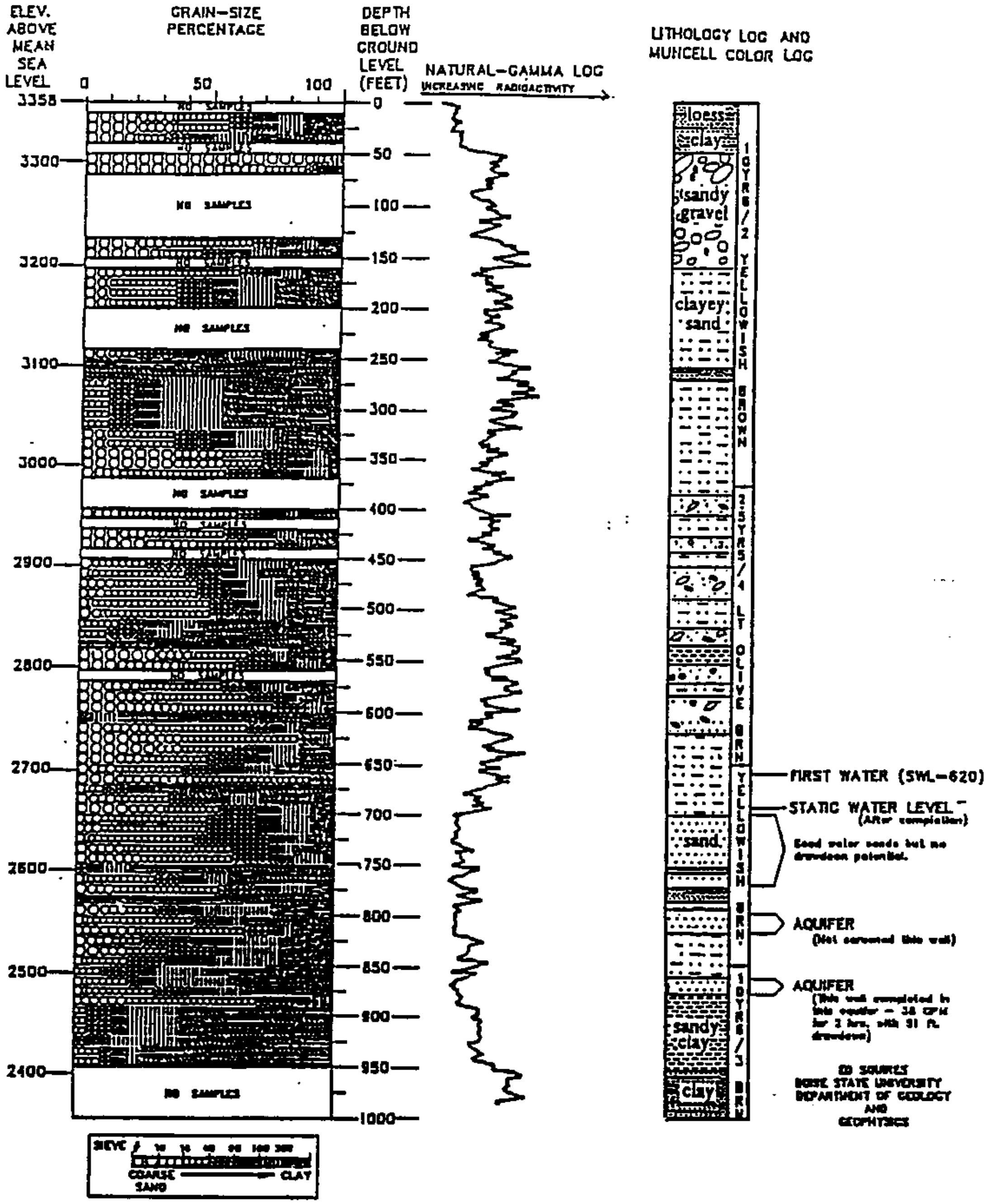


SUBSURFACE PROFILE 7

BOISE WATER CORPORATION
COLUMBIA TEST WELL
11/26/1990

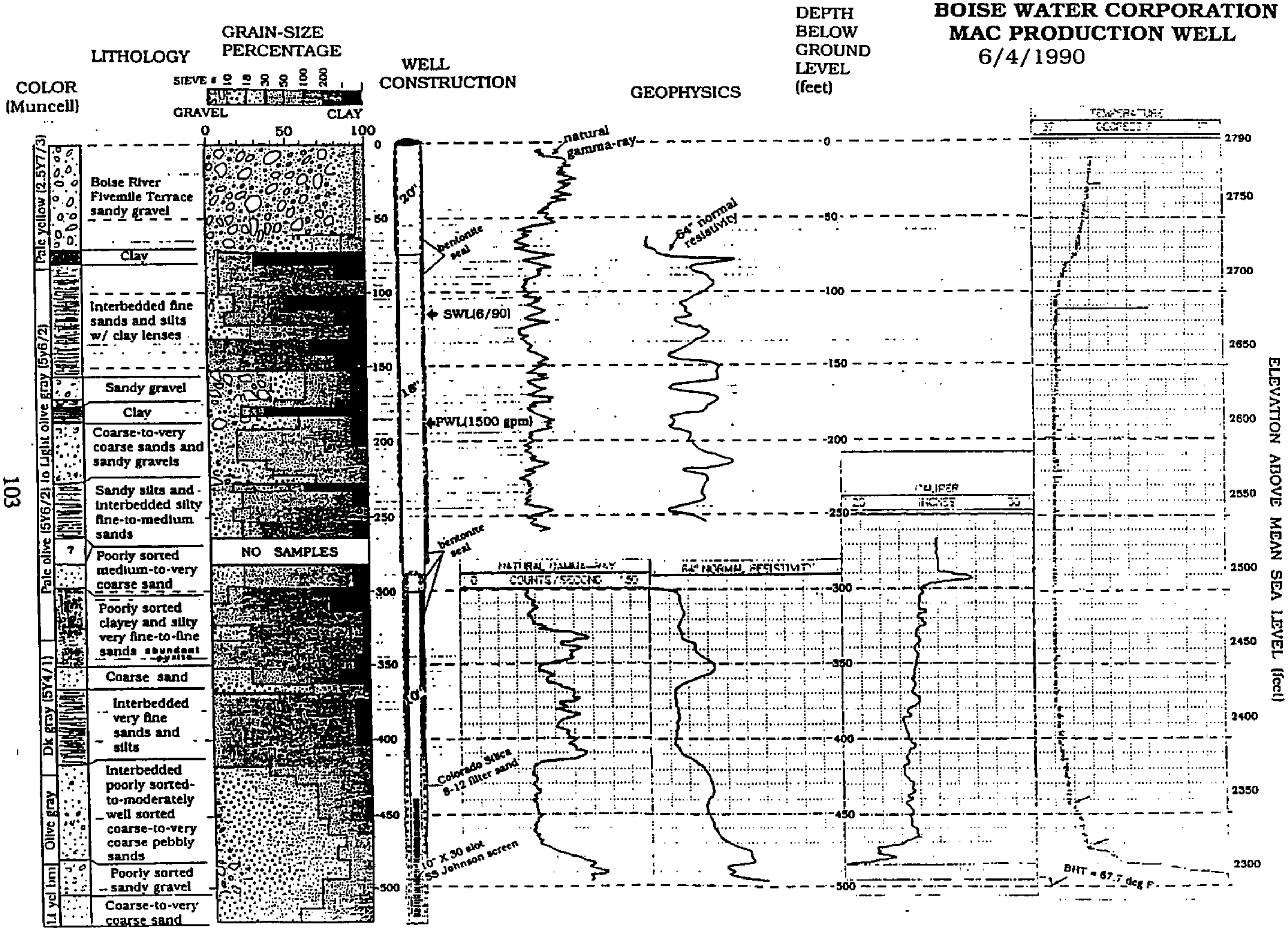


DEPARTMENT OF TRANSPORTATION EAST PORT OF ENTRY WELL

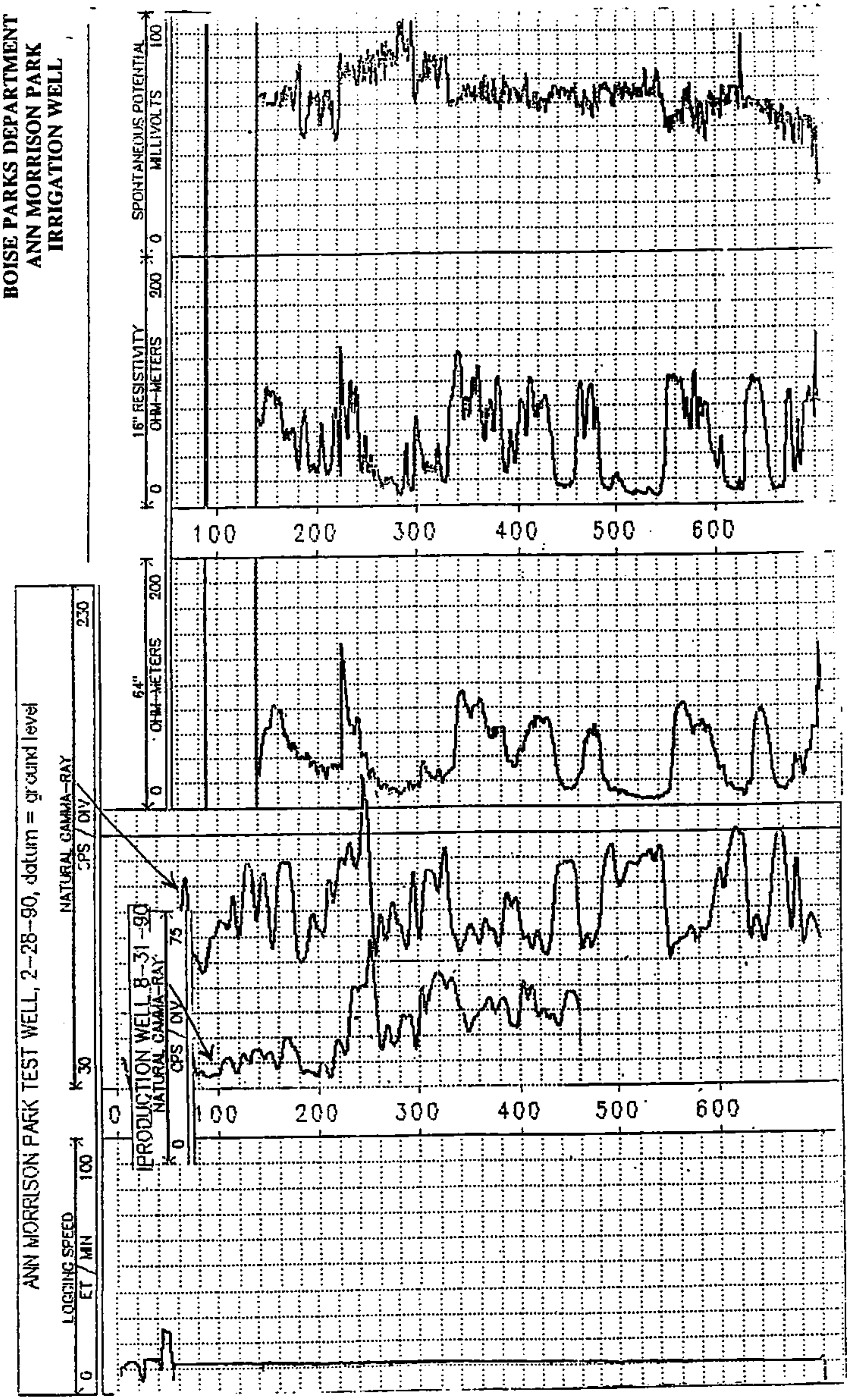


Natural-gamma geophysical log and cuttings-analysis log of grain-size percentage and lithology for the 1988 State of Idaho, Dept. of Transportation, Port of Entry well located ten miles east of Boise, Idaho along I-84. The grain-size percent log is an attempt to be totally objective in the description of samples. Some of the material may be cavings, and some may be a mix of interbedded silts and sands. Log preparation was as follows: 200cc of sample cuttings, taken at 5 foot intervals, during cable-tool drilling were washed through a stack of sand sieves. Percentage of material retained on each sieve was visually estimated. Reported sand has been discounted for shale chips and mud lumps. The amount of material that washed through a no. 200 sieve is reported as the silt and clay percentage.

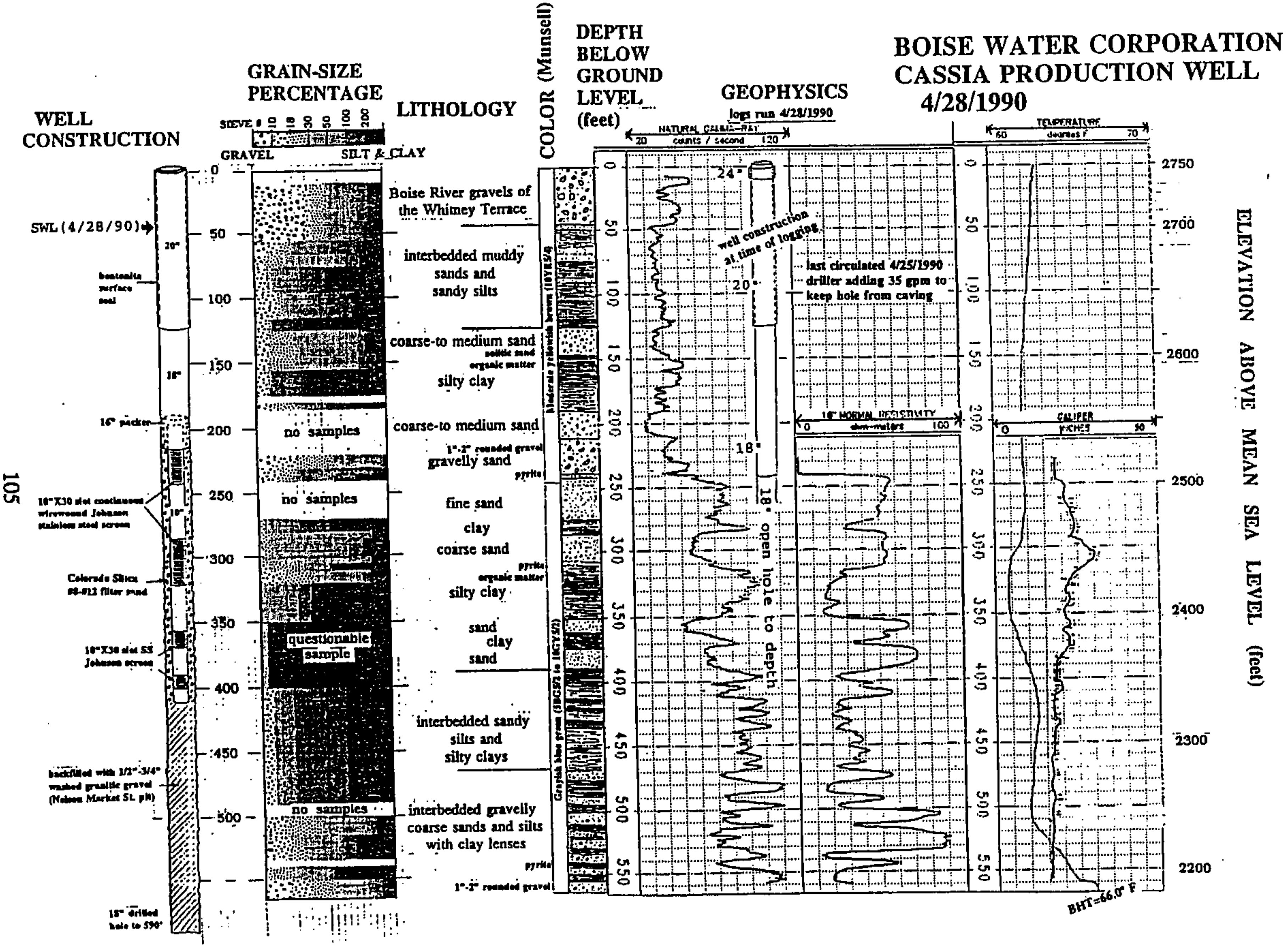
BOISE WATER CORPORATION
MAC PRODUCTION WELL
6/4/1990



BOISE PARKS DEPARTMENT
ANN MORRISON PARK
IRRIGATION WELL

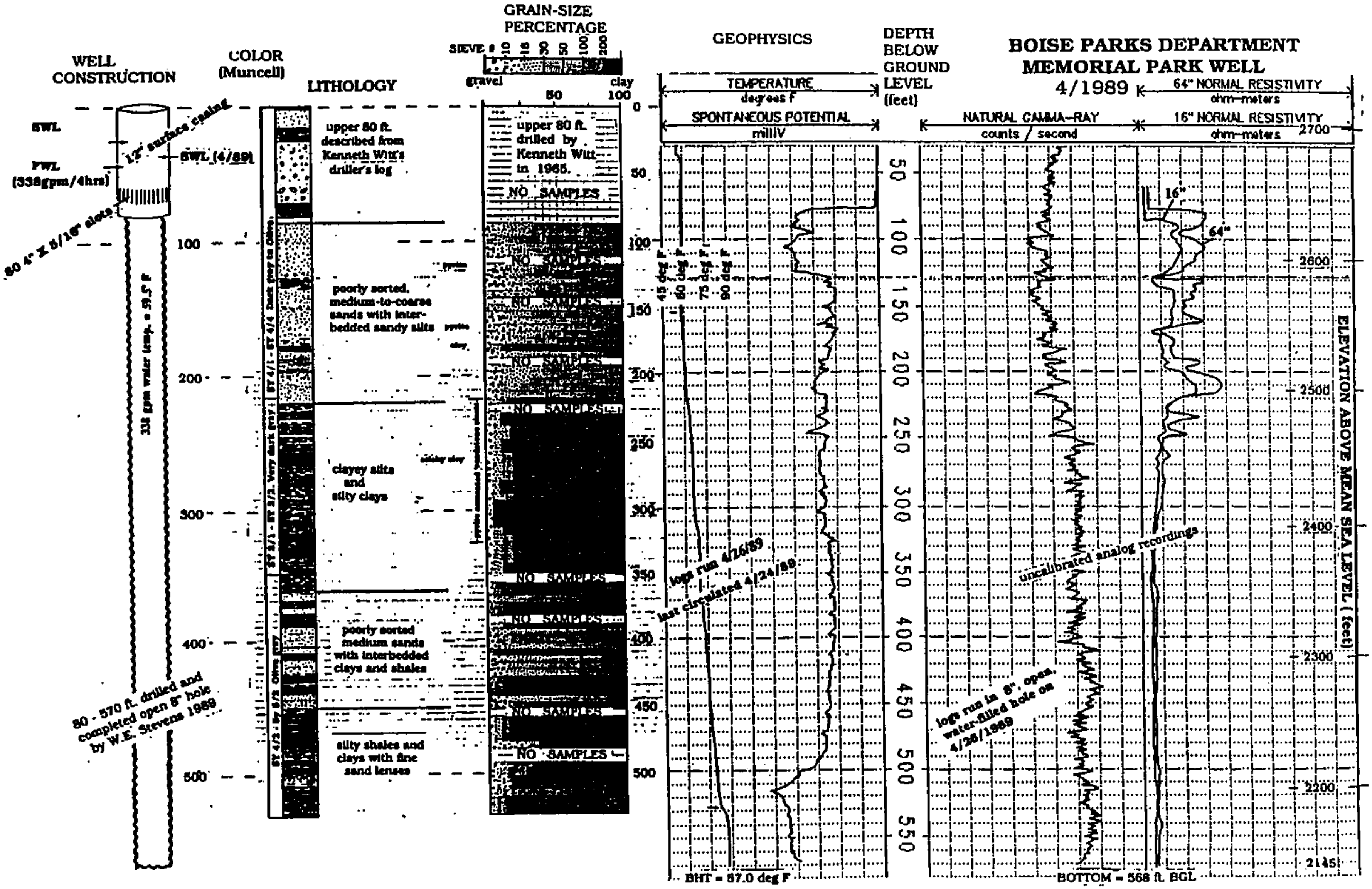


BOISE WATER CORPORATION CASSIA PRODUCTION WELL 4/28/1990

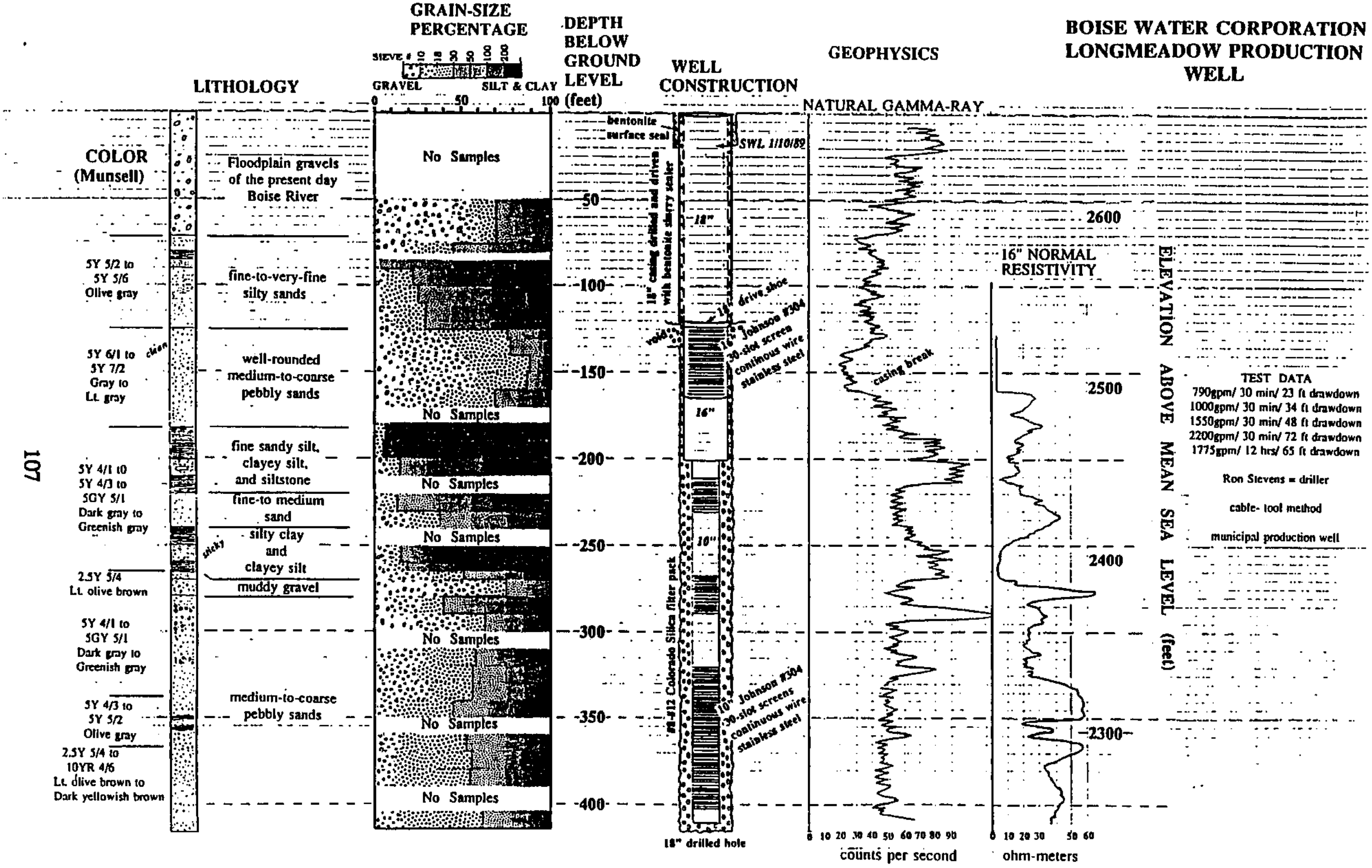


BOISE PARKS DEPARTMENT MEMORIAL PARK WELL

4/1989



BOISE WATER CORPORATION LONGMEADOW PRODUCTION WELL



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