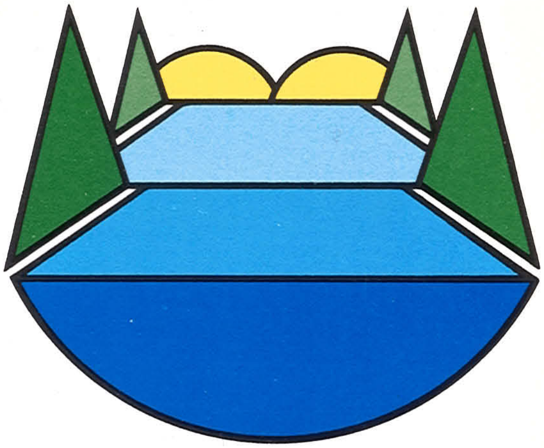

Earth Sciences Report 82-2

Groundwater Hydrology of the
Pine Lake Research Basin, Alberta
A Preliminary Analysis

by G. Garven

Alberta
RESEARCH COUNCIL

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ABSTRACT

The Pine Lake research basin is a 230 km^2 (90 sq mi) parkland in south-central Alberta. Various types of geologic, geophysical, and hydrologic data were used to evaluate the hydrogeology of the research basin.

Permeable sandstone, mudstone, and coals of the thick Paskapoo Formation underlie the study area. The major, shallow sandstone aquifers have hydraulic conductivities between 0.5 to 2.5 m/day (10 to 50 igpd/ft^2). A thin mantle of glacial drift characterizes the surficial geology.

The water-table configuration is a subdued replica of the topography. Groundwater flows from broad recharge areas on the main divides to discharge areas in the valley bottom. Sodium-bicarbonate groundwater, which dominates the basin, evolved primarily through carbonate dissolution and cation exchange processes. Correlation between hydrochemical facies and groundwater flow patterns is poor. The groundwater regime in the research basin is most appropriately treated as a steady-state, regionally unconfined system in a heterogeneous and anisotropic rock medium. Natural basin yield was calculated from a finite-element simulation as 55 m^3/day/m (4000 igpd/ft).

This analysis is designed as a framework for instrumentation and a guide for future hydrologic studies in the Pine Lake area. Recommendations for instrumentation and future studies include installation of a piezometer network, further aquifer testing and numerical modelling of saturated-unsaturated groundwater flow and hydrochemistry.

INTRODUCTION

The Alberta Research Council's Groundwater Department planned for the establishment of an experimental research basin several years ago. The Pine Lake area in the south-central part of the province was recently chosen for this purpose, largely because of its good access, varied hydrogeologic conditions, and the potential of practical application of study results to the local area.

Tóth (1977) described the main purposes of the Pine Lake research basin as follows: (1) to investigate and measure subsurface components of the hydrologic cycle in a parkland environment; (2) to develop standard, or improved, methods of evaluating subsurface hydrologic parameters; and (3) to establish a research and training area where test results can be accumulated over a substantial period of time.

The objective of this report is to evaluate the groundwater hydrology of the proposed Pine Lake research basin. This study is based solely on field reconnaissance observations, existing subsurface data, and the results of a small exploration program. The report will develop a framework for future instrumentation of the basin and detailed analysis.

ACKNOWLEDGMENTS

A major portion of the data was collected while the author was employed as a research officer (summers of 1978, 1979) with the Groundwater Department of the Alberta Research Council. Much of the analysis and interpretation was performed in the interim period at the University of Arizona where the author was a graduate student. The author is grateful for the research and field experience as well as for the permission of the Research Council to use department-generated data as a basis for a master's thesis (Garven, 1980).

The author would also like to thank the staff of the Groundwater Department whose assistance, directly or indirectly, aided the Pine Lake research

basin project. J. Tóth supervised the work, gave invaluable advice, and provided discussion on the significance of field mapping groundwater phenomena in hydrologic investigations. E.J. Wallick offered enlightening discussions on the hydrogeology and hydrochemistry of the Pine Lake area. G.M. Gabert's assistance was sincerely appreciated and W. Ceroici extended much help on the project.

S.N. Davis generously assisted and advised the author throughout his academic program at the University of Arizona. R.A. Freeze, J.W. Harshbarger, S.P. Neuman, and E.S. Simpson also provided valuable advice on several aspects of the project.

D.W. Organ of Chevron Standard Limited supplied structure testhole electric logs for the entire study area. R. Rahmani of Coal Geology, Alberta Research Council, supplied logs for a number of testholes in the Pine Lake area. Their special contribution is gratefully acknowledged.

Testhole drilling was most competently handled through Lousana Water Wells Ltd., Lousana, Alberta. The author would also like to express his sincere thanks to the staff of the Groundwater Department who aided the field projects, in particular G. Sjostrom and A. Beerwald. Cooperation of the residents in the Pine Lake area facilitated the field mapping and exploration programs.

Finally, the writer would like to express his appreciation to M. Madunicky who was a great help in drafting and preparing the text figures. Sincere thanks also go to J. Probert and L. Radke for typing the draft and preparing the tabulated data.

LOCATION AND EXTENT OF STUDY AREA

Pine Lake is located in what is described as the Western Alberta Plains, in south-central Alberta, as shown in figure 1. It is approximately 125 km (80 mi) north-northeast of Calgary.

The research basin, itself, is about 230 km² (90 sq mi) of the upper portion of the Ghostpine Creek drainage basin, as shown in figure 2. It lies within the area of townships 35 to 37, and ranges 24 to 26, west of the fourth meridian, between 113°17′ and 113°43′ west longitude, and 51°58′ and 52°14′ north latitude. The southern boundary of the basin is partially arbitrary.

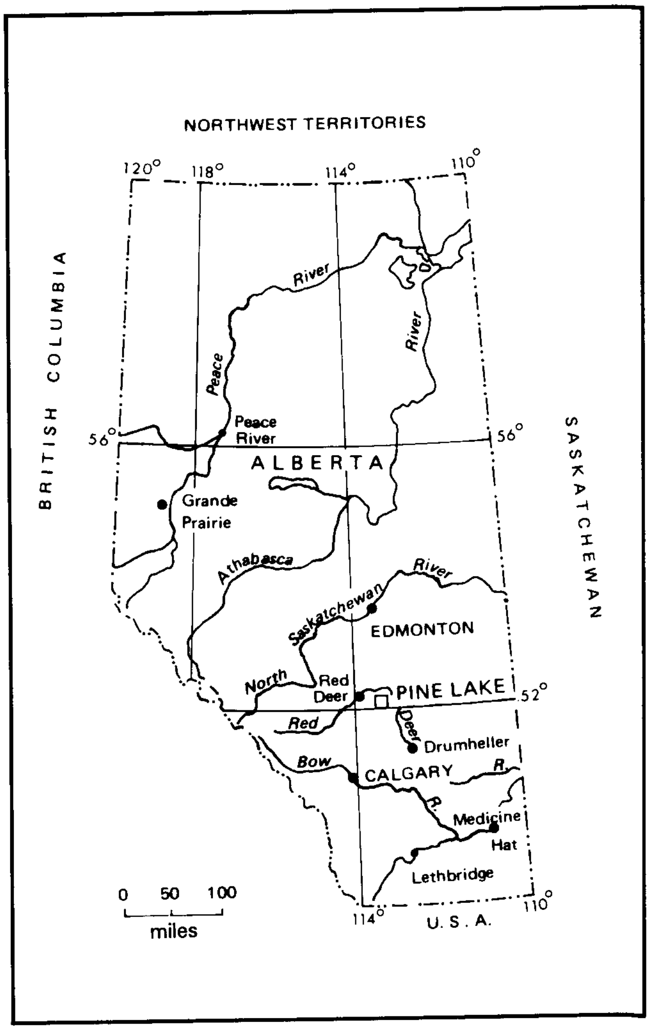

FIGURE 1. Location of Pine Lake, Alberta.

PREVIOUS WORK

Several groundwater resource surveys have been conducted in south-central Alberta, but the Pine Lake area has not previously undergone detailed hydrogeological investigation. Early studies that partly included the Pine Lake basin were those of Latour (1947) and Stalker (1950), of the Geological Survey of Canada. They described geology and groundwater resources for each township in the

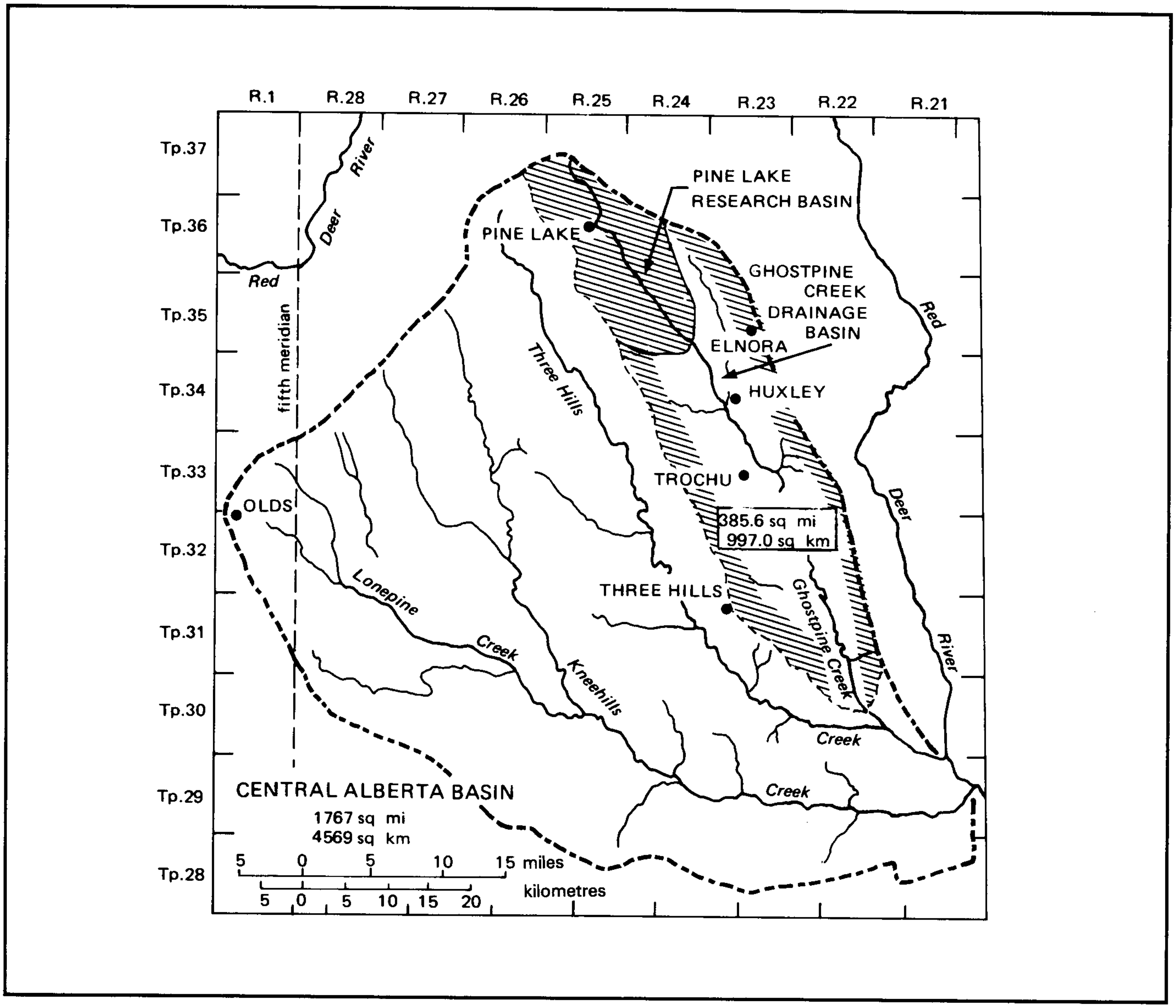

FIGURE 2. Map of central Alberta showing regional drainage and location of the Pine Lake research basin.

respective map areas, using a well-inventory approach. Maps showing surficial geology and topography, with location of wells, were published at a scale of 1 inch to 3 miles. Basic data consisted of well records and yields, aquifer types, use, and water quality. The information from these reports has been of great value to the present study.

The Alberta Research Council has published the most recent analysis of the regional groundwater resources. Le Breton (1971) and Borneuf (1972) completed studies on the reconnaissance hydrogeology of the Red Deer and Drumheller map sheets, respectively. Maps published by these authors are on a scale of 1:250 000 and cover about 13 000 km^2 (5000 sq mi). The maps, and several regional cross sections, illustrate the generalized geology to a depth of about 300 m (1000 ft), direction of groundwater flow, subsurface hydrogeologic properties, groundwater probability, hydrochemistry, locations of springs, and flowing wells, and relevant meteorological data. The Pine Lake research basin comprises a small part of the total area investigated by Le Breton (1971). Furthermore, only a very small portion is in the area mapped by Borneuf (1972).

There are detailed groundwater studies of areas adjacent to the Pine Lake basin, where similar hydrogeological conditions exist. Tóth (1966a) mapped and interpreted groundwater phenomena in a section of the Ghostpine Creek Valley near Trochu (see fig. 2), southeast of the Pine Lake research basin. Tóth (1968) also made an extensive investigation of the Three Hills area, which included a portion of the Ghostpine Creek drainage basin, downstream of the 1966 study. Gabert (1975) made an extensive study of the hydrogeology of the Red Deer area. The southeast corner of Gabert's map area partially overlaps the northwestern region of the Pine Lake study area. The interpretations made by these authors, and their methods of analysis, have been invaluable to the present study.

TYPE, SOURCE, AND TREATMENT OF DATA

The location and types of basic data used in the present study are shown in figures 3, 4 and 5. The location map of general well data (fig. 3) represents all existing geologic and hydrologic information on the Pine Lake research basin available in the files of the Groundwater Data Center, Alberta Research Council. Many well records published by Latour (1947) are represented on this map.

Most well data shown (fig. 3) come from reports submitted by water well drillers over the past 15 to 20 years. These records describe well construction, details of completion, static water levels, lithologies, and recovery measurements of water levels after a brief bail test. Time-drawdown data from pump or bail tests are rare. Water chemistry analysis of samples submitted to rural health authorities by private well owners are numerous. The major anions and cations are usually reported, along with total dissolved solids, hardness, alkalinity, conductivity, fluorides, and iron. Other information obtained from the data center files included reports of water levels and details of well construction from well inventory surveys, seismic shothole reports from exploration companies, and a few electric logs from oil or gas wildcat wells. Records were also available on three observation wells, equipped with continuous water level recorders. Groundwater hydrographs are available from 1963 to the present. Considerable time and effort was devoted to interpreting all well records and the results are summarized in appendix A. Appendix B is a schedule listing water chemistry analyses. Pertinent data for any given well location on the map can be found listed under its index number in either schedule.

A second major type of data used in the Pine Lake study consisted of observations and chemical analyses of water samples obtained during the field survey in the summer of 1978. Figure 4 illustrates the type and distribution of field observations. Descriptions of these features were recorded in a set of field notes. Water samples from wells, springs, and surface water were collected throughout the research basin. The results of the chemical analyses of these samples are listed with the earlier data in appendix B.

The third major source of data used to evaluate the Pine Lake area were logs of deep wells (fig. 5), usually drilled for reasons other than for water supply. Structure testhole electric logs are a large portion of the deep geologic information for the Pine Lake basin. These testholes were drilled in the early 1950s to obtain shallow structural-stratigraphic data that would indicate potential oil-or-gas-producing formations at much greater depths. Chevron Standard Ltd. and the Energy Resources Conservation Board, both of Calgary, provided electric self-potential and resistance logs for testholes. Figure 5 also shows the locations of testholes drilled for a coal study by the Alberta Research Council. A lithological log and various types of geophysical logs were available for these holes. Also on this map are locations of oil or gas wildcat wells for which geophysical logs are available. Unfortunately, these logs are of little value to this study because the logging usually stopped at a depth of around 200 to 250 m (600 to 800 ft), depending on the length of the surface casing. Occasionally, a radioactivity-type log can be used for shallow stratigraphic interpretation.

Elevations of water wells were estimated from a topographic base map with 25-ft contours. Ground elevations of seismic shotholes, structure testholes, and oil or gas wildcat wells reported on the logs are presumed to have been surveyed. The only other hydrogeologic data generated by this preliminary study consists of the test drilling and aquifer testing at four sites in the research basin.

GEOGRAPHIC CONSIDERATIONS

TOPOGRAPHY

The Pine Lake research basin is located within a regional series of elongate ridges and valleys trending northwest-southeast in a portion of the Western Alberta Plains physiographic region (fig. 2). By far the most prominent regional topographic feature is the incised valley of the Red Deer River, which in places is over 150 m (500 ft) deep. Bedrock geology and differential erosion are responsible for the major topographic features in this region. The Pleistocene glaciations created many small, local features and modified the original topography of the bedrock. Figure 6 shows the topography and physiographic features of the Pine Lake basin. Elevations in the research basin range from over 1050 m (3450 ft) in the rugged ridge area at the northwest end, to less than 850 m (2850 ft) where Ghostpine Creek leaves the study area in the southeast.

DRAINAGE

Compared to other parts of the Canadian prairie, regional drainage in south-central Alberta (fig. 2) is relatively good. Several authors have noted the marked parallelism and regular spacing of the four main creeks — Lonepine, Kneehills, Threehills, and Ghostpine. Tóth (1962, 1968) summarized the general characteristics of these creeks as shallow, underfit, meandering streams of a barely perennial nature whose discharge is quite variable.

The surface water drainage divide was used to define the boundary of the Pine Lake basin. This boundary was especially difficult to determine in hummocky areas and, furthermore, the research basin is not hydrologically closed because the southern boundary is not a surface drainage divide in the true sense. The southern boundary lies in a convenient location to limit the size of the research area.

Pine Lake is the only major surface water body in the Ghostpine Creek drainage basin (fig. 7). Two streams drain the northern part of the basin above Pine Lake. They do not directly drain the highly elevated region, but rather their head waters are located along the margin of hummocky areas. A subdued ridge, extending from the northern uplands, acts as a drainage divide between these streams down to their confluence near Pine Lake. Stream channels also drain broad areas of boggy lowland on both sides of the lake. In turn, Pine Lake is the reservoir for Ghostpine Creek. The creek meanders as an underfit stream with its bed incised into a wider preglacial valley. Tributaries to Ghostpine Creek have eroded significant drainage channels back into the main ridges. Several ponds and small lakes are found along the creek valley and some of its tributaries.

SOILS

The Pine Lake basin lies almost entirely within the Black Soil zone of Alberta. Detailed descriptions of soil types can be found in the report by Bowser, Peters, Newton (1951), and need not be repeated here. For the most part, soils in this area are well-drained. Salt-affected profiles were only observed in the southern part of the basin, along Ghostpine Creek. Strong correlation between soil texture and glacial geology exists throughout the research basin.

VEGETATION

Originally, the Pine Lake area was completely covered by typical parkland vegetation (Government and University of Alberta, 1969). Today, about 50 to 60 percent of the research basin has been cultivated and cleared. Nevertheless, the native parkland environment is still quite apparent, especially in the rougher terrain and along parts of the drainage system where farming is not yet feasible. The most important hydrological feature is the abundance of phreatophytes in depressional areas and drainage ways, which no doubt significantly influence the subsurface hydrology.

CLIMATE

Fortunately, a meteorological station exists in the Pine Lake research basin and is located in Lsd 4 Sec 10 Tp 37 R 25 W4Mer. Although observations of temperature and precipitation have only been made since 1960, they are the best data currently available and probably represent conditions in at least the northern half of the research basin. Observations recorded at a station further south

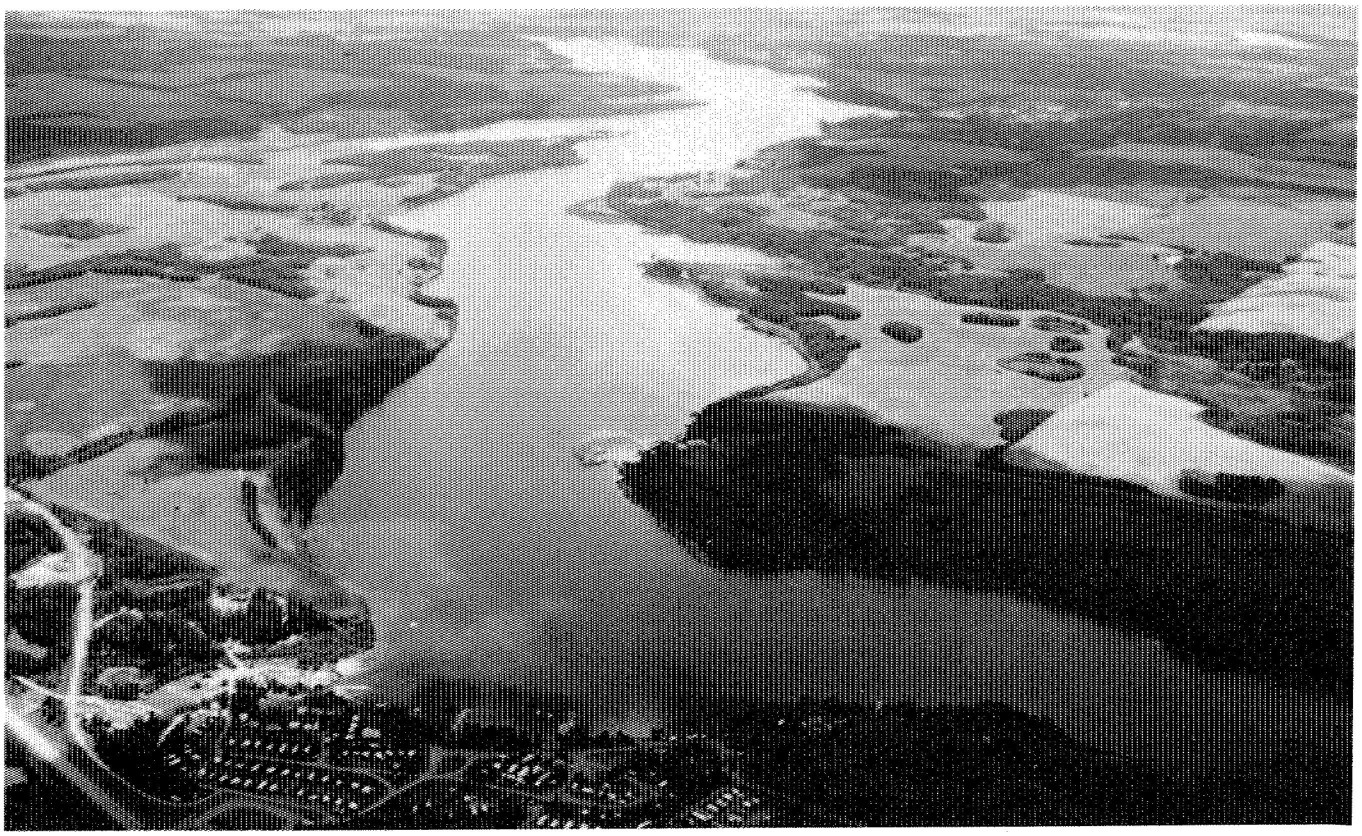

FIGURE 7. Aerial view of Pine Lake, looking south from north end of lake.

in the Ghostpine Creek valley near Trochu (fig. 2) may be more characteristic of the climatic conditions at the south end of the research basin than the Pine Lake station. For that reason, data from both the Pine Lake and Trochu Equity stations are presented in tables 1, 2 and 3, which contain mean monthly values of precipitation, temperature, and potential evapotranspiration between 1941 and 1970.

Based on the available information, mean annual precipitation in the Pine Lake research basin probably varies from about 41 cm (17 in) in the southern part of the area, to over 48 cm (19 in) in the northern uplands. This estimate agrees quite closely with climatic maps of Alberta prepared by Longley (1968) for the record from 1931 to 1960. Of the total mean annual precipitation shown for the Pine Lake station in Table 1, rainfall was 36.7 cm (14.4 in) and mean snowfall was 126.5 cm (49.8 in) (Environment Canada, 1973).

The values of potential evapotranspiration are contained in table 3. They were calculated using the empirical method of Thornthwaite (1948). The mean annual potential evapotranspiration for the Pine Lake research basin is about 53 cm (21 in) in the south to less than 51 cm (20 in) in the northern region. The estimated average annual potential evapotranspiration is 50 to 56 cm (20 to 22 in) for the general region; actual evapotranspiration is 41 to 46 cm (16 to 18 in) (Government and University of Alberta, 1969). Figures 8 and 9 describe the relationship between precipitation and potential evapotranspiration for an average year in the Pine Lake area. These Thornthwaite diagrams show how precipitation exceeds potential evapotranspiration from mid-October to mid-April.

TABLE 1.

Mean monthly precipitation, Pine Lake research basin (1941-1970)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Pine Lake cm	2.13	1.80	1.63	3.43	5.87	8.51	8.00	6.99	4.83	2.59	1.93	1.56	49.28
in	0.84	0.71	0.64	1.35	2.31	3.35	3.15	2.75	1.90	1.02	0.76	0.62	19.40
Trochu Equity cm	1.93	1.80	1.91	2.90	3.73	7.47	7.11	5.59	3.53	2.31	1.65	1.73	41.66
in	0.76	0.71	0.75	1.14	1.47	2.94	2.80	2.20	1.39	0.91	0.65	0.68	16.40

TABLE 2.

Mean monthly temperatures, Pine Lake research basin (1941-1970)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Pine Lake °C	-14.6	-10.4	-6.1	2.8	9.4	12.8	15.7	14.3	9.6	4.5	-4.4	-10.3	1.9
°F	5.7	13.2	21.0	37.1	48.9	55.1	60.3	57.7	49.2	40.1	24.0	13.4	35.5
Trochu Equity °C	-14.3	-10.0	-5.4	3.5	10.3	14.7	17.3	16.4	11.1	5.1	-4.7	-10.5	2.8
°F	6.3	14.0	22.3	38.3	50.6	58.4	63.1	61.5	52.0	41.1	23.5	13.1	37.0

TABLE 3.

Mean monthly potential evapotranspiration, Pine Lake research basin (1941-1970)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Pine Lake cm	-	-	-	2.34	7.45	9.82	11.78	10.00	6.04	2.81	-	-	50.24
in	-	-	-	0.92	2.93	3.87	4.64	3.94	2.38	1.11	-	-	19.79
Trochu Equity cm	-	-	-	2.48	7.58	10.64	12.47	10.88	6.47	2.81	-	-	53.33
in	-	-	-	0.98	2.98	4.19	4.91	42.8	2.55	1.11	-	-	21.00

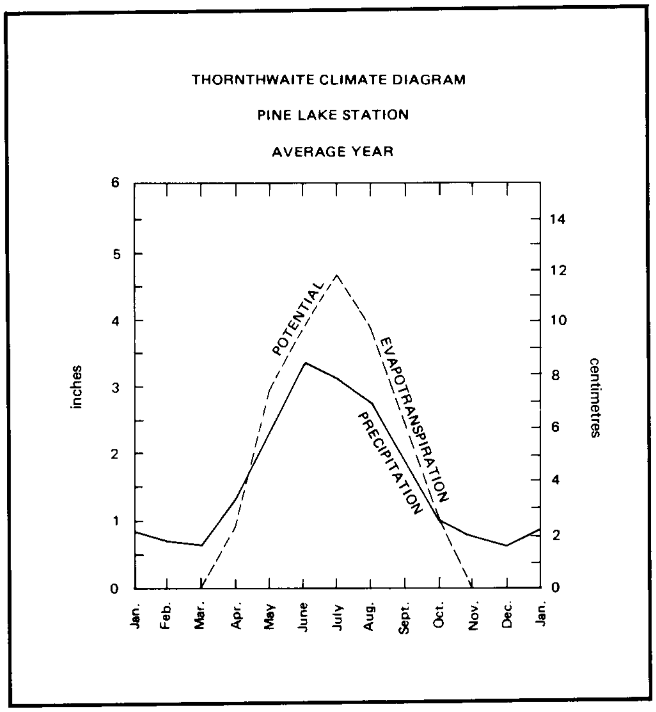

FIGURE 8. Graphical representation of climate at the Pine Lake meteorological station.

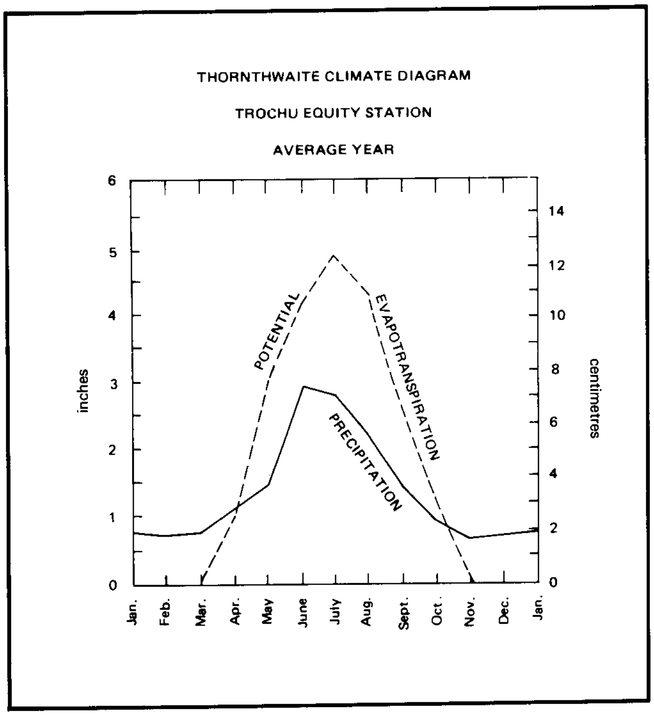

FIGURE 9. Graphical representation of climate at the Trochu Equity meteorological station.

PHYSIOGRAPHIC FACTORS OF GROUNDWATER RECHARGE

The most important physiographic factor of groundwater recharge on the Canadian plains is climate. Figures 8 and 9 show that for an average year, potential evapotranspiration exceeds precipitation from April to October, thereby posing a major constraint to groundwater recharge. During the rest of the year, precipitation does exceed potential evapotranspiration, but the long cold winters effectively limit the period during which surface water can actually infiltrate into the ground and recharge the groundwater system. In the Pine Lake area, these potential recharge conditions occur during early October and late April when the ground is not frozen. Because precipitation is low in the fall (probably sufficient only to restore soil moisture), a major groundwater recharge is unlikely at that time. Only in late April to early May is the climate conducive to groundwater recharge. In this period, surface water is abundant from melting snow packs and high precipitation, evapotranspiration is low, and infiltration is not impeded by frozen ground. Even during periods of early thaw, frozen or partially frozen ground is probably not impermeable, so infiltration can take place (Williams and Burt, 1974).

A second major physiographic factor of groundwater recharge is topography. The water table, for instance, is a subdued replica of the topography. Regional topographic highs or uplands usually act as "recharge" areas because groundwater is naturally at a higher hydraulic head, so motion is directed towards areas of lower potential energy. Topographic lows are often discharge areas for groundwater flow. Another aspect of the effect of topography is that the unsaturated zone is likely to be considerably thicker in upland regions than in regional discharge areas. This has significant implications when interpreting groundwater chemistry, or the role of infiltration and unsaturated flow, as a component of the subsurface hydrologic cycle.

Drainage of the land has great importance in determining the actual quantities of precipitation that will be available for groundwater recharge. Some parts of the basin have integrated drainage and a considerable portion of the precipitation and snowmelt could be lost by runoff. In large areas of hummocky upland, drainage is quite poor and surface water is detained in sloughs. Surface water in these areas has a much greater opportunity to infiltrate and recharge the saturated zone. The abundant growth of phreatophytic vegetation around these depressions combined with high summer evaporation will limit this recharge process mainly to early spring and to extended periods of summer rainfall. In the intermediate and lowland areas, local depressions probably act as groundwater discharge points, at least over most of the summer, but may contribute intermittently to groundwater recharge (Meyboom, 1966b).

The nature of the soils also influences groundwater recharge. In areas where drainage is poor, infiltration rates determine recharge rates. Infiltration and percolation are greatest in sandy-textured soils; in loams, surface water is more vulnerable to runoff and evapotranspiration.

SURFACE WATER HYDROLOGY

Because surface water is an integral part of the hydrologic cycle, it has significant importance in basin-wide evaluation of the subsurface hydrology. Although data is limited, some general observations and interpretations of the surface water hydrology in the Pine Lake research basin can be made.

STREAMFLOW

All streams in the research basin, including Ghostpine Creek, are intermittent, but are sometimes interrupted by perennial parts of the reach. Although they are shallow and narrow, these streams contain natural depressions that pond surface water, leading to an increase in evaporation losses. Furthermore, a large part of the annual precipitation ends up as streamflow, especially during periods of spring melt and summer storms.

The drainage area of the Ghostpine Creek basin, associated with the gauging station near Huxley*, is approximately 520 km^2 (200 sq mi). Although a major portion of this area is fairly well drained, the tracts of hummocky land in the basin do not drain well. Surface runoff in the hummocky areas usually amounts to overland flow into sloughs. Because the streamflow record is so short, and only a crude estimate of mean annual runoff was considered, the area of the basin actually contributing to total runoff was not determined. Based on the streamflow records, total runoff for 1967 amounted to 7.13 x 10^{6}m^3 (5780 ac-ft), whereas the annual runoff for 1969 was 1.36 x 10^{7}m^3 (11 000 ac-ft). Converting these figures to a depth over the 520 km^2 (200 sq mi) drainage area, annual runoff for 1967 is 1.37 cm (0.54 in) and for 1969 is 2.62 cm (1.03 in). The 1968 record was incomplete, so the runoff has not been calculated. With such a short period of record, it is difficult to judge how representative these figures are of the mean basin runoff.

The creek is almost completely frozen during the winter and therefore discharges can only be measured between spring thaw and late fall. As the 1967 hydrograph (fig. 10) illustrates, streamflow in Ghostpine Creek is intermittent. The major runoff in April depends completely on meltwater from the winter snowpacks. Although the runoff begins to recede after thaw, substantial rainfall in May, and especially June, briefly sustains streamflow. By early July, however, the low precipitation and high evapotranspiration rates deplete streamflow until it is almost negligible. By October, evapotranspiration losses have decreased so much that groundwater flows and minor amounts of rainfall only sustain daily streamflows of less than 0.014 m^3/s (0.5 ft^3/s).

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*Quantitative streamflow records in the Ghostpine Creek drainage basin are scanty and for that part of the drainage basin in the Pine Lake research basin, nonexistent. Runoff observations have only been made for Ghostpine Creek. Measurements of creek stage were recorded for 1962 to 1966, but were not published. A discharge-type gauging station was established on Ghostpine Creek near Huxley (fig. 2) where discharge was recorded for the years 1967, 1968, and 1969. This gauging station was subsequently abandoned.

The complete streamflow records for the three years of discharge measurements are given in Environment Canada (1974). Table 4 is a summary of the streamflow data for the Ghostpine Creek station near Huxley. For purposes of illustration and discussion, the 1967 streamflow hydrograph and its corresponding hyetograph have been plotted in figure 10.

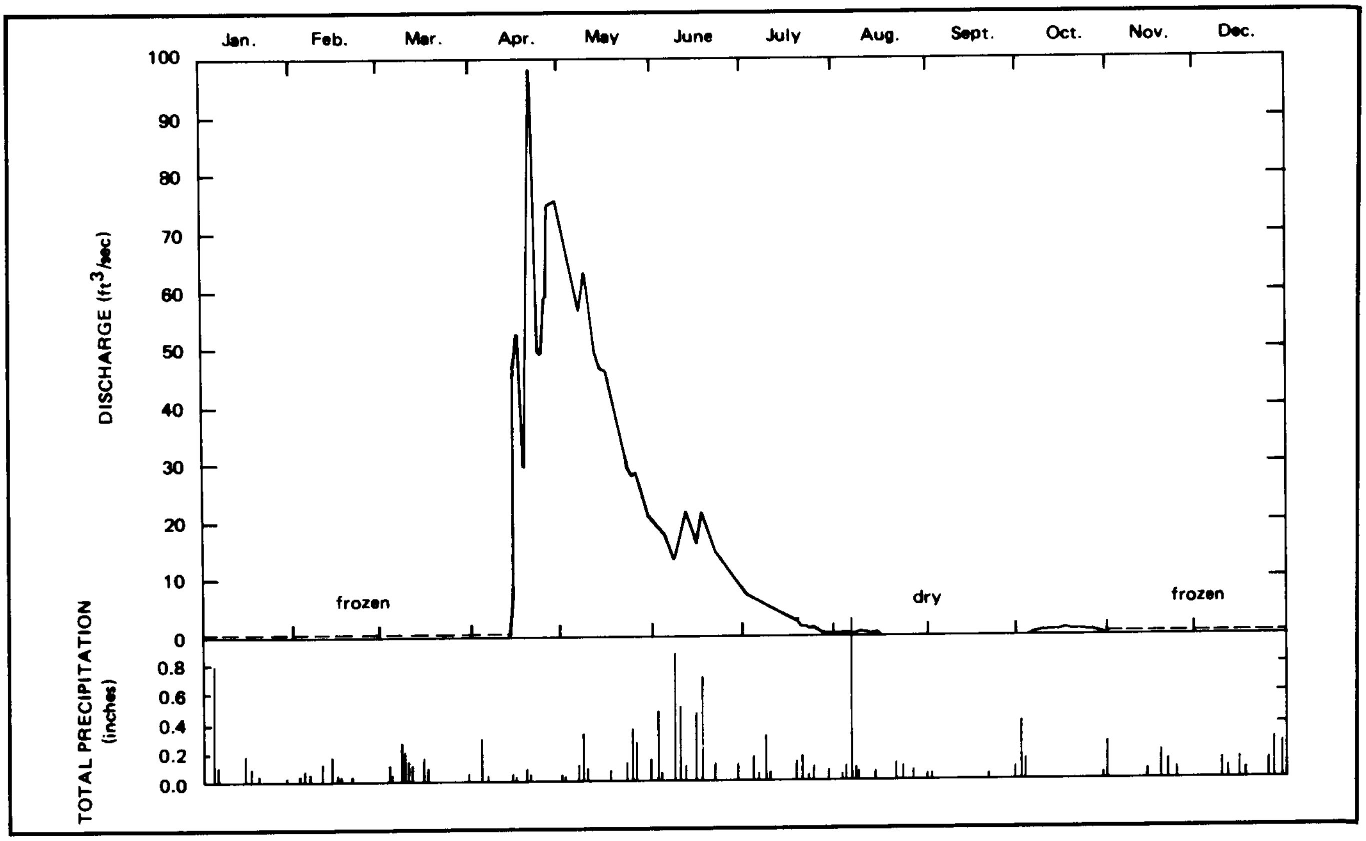

FIGURE 10. Ghostpine Creek streamflow hydrograph and Pine Lake station hyetograph, 1967.

The above description of streamflow indicates that the baseflow component of runoff is very small in the Ghostpine Creek drainage basin. In other words, groundwater discharge into the streams of the basin is often only sufficient to meet the demands of the frost-free months.

The actual amount of baseflow, or groundwater discharge, that contributes to streamflow in the April to June period is difficult to assess because of the large volume of surface runoff. Freeze (1969a) used minimum monthly discharges to estimate annual baseflow for several streams in a drainage basin in Saskatchewan. He pointed out that the baseflow in these intermittent streams may or may not represent total groundwater discharge, but that such figures could be correlated with mean annual groundwater recharge.

In any event, this procedure amounts to 2.2 x $10^6 m^3$ (1780 ac-ft) or 0.43 cm (0.17 in) over the drainage area associated with the Ghostpine Creek gauging station for the 1967 record. The figures for the 1969 record are 1.4 x $10^6 m^3$ (1120 ac-ft) or 0.27 cm (0.11 in) respectively. Whether or not these values accurately represent groundwater discharge is debatable.

LAKES AND SLOUGHS

Comparison of aerial photographs taken in 1975 with topographic maps of 1970 and 1959 show that all lakes in the Pine Lake research basin are permanent bodies of surface water, although a few have varied slightly in area over the past 25 years. Pine Lake is the largest reservoir of surface water.

Figure 11 shows the results of a 1967 hydrographic survey of Pine Lake by the Surveys Branch, Alberta Department of the Environment.

Lake levels have been recorded since 1965, but daily observations, based on a 1.5 m fiberglass staff gauge at the north end of Pine Lake, have only been available since 1973. The lake level

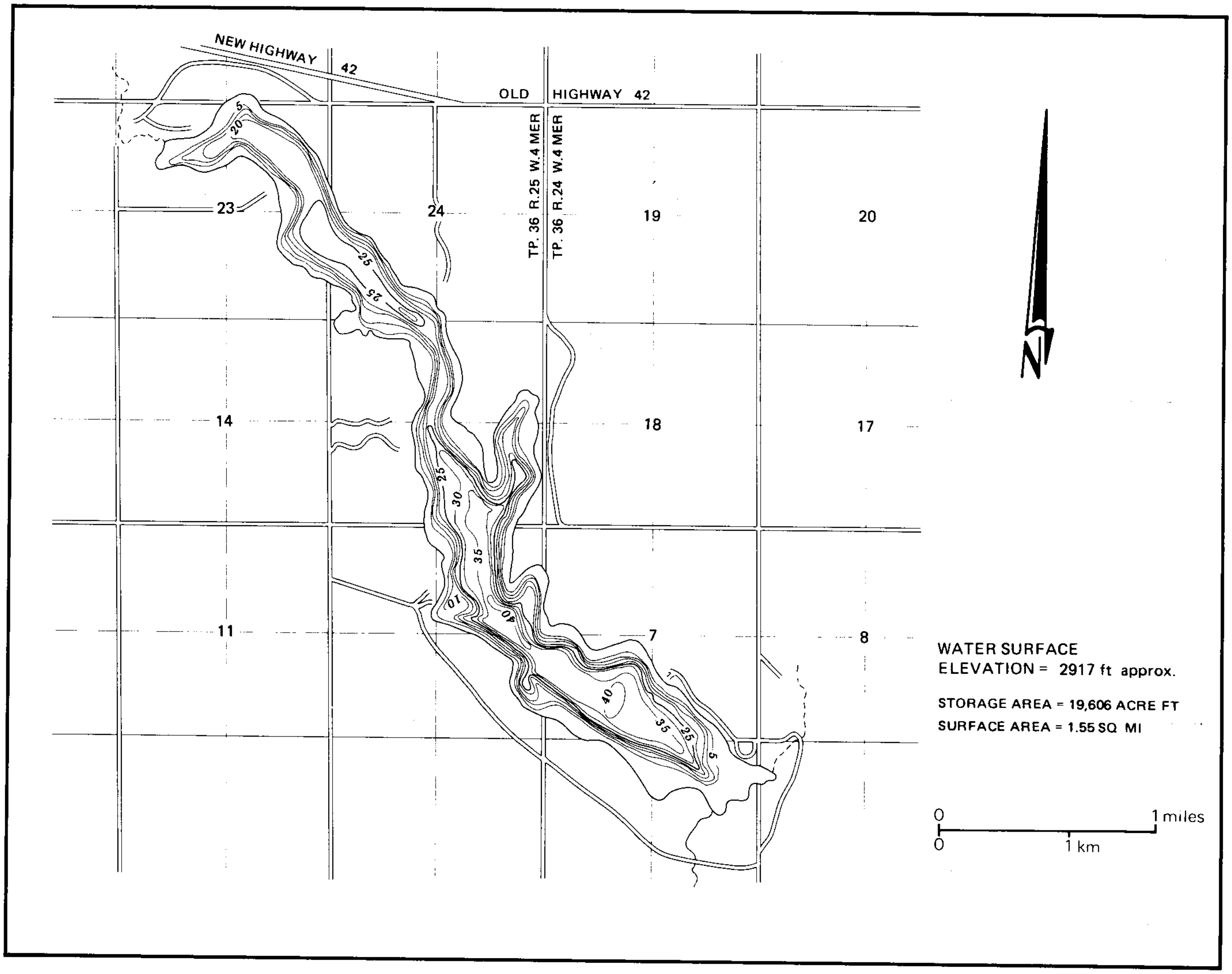

FIGURE 11. Hydrographic map of Pine Lake (after Surveys Branch, Alberta Department of the Environment, 1967). Contours represent lake depth, in feet.

hydrographs for the years 1973, 1975, 1976, and 1977 are shown in figure 12. The 1974 record is incomplete, so has not been plotted. Pine Lake is completely frozen over from about November to the end of April.

A recession curve analysis of the lake level hydrographs is shown in figure 12 and the results tabulated in table 5. The net evaporation from June 1 to October 1 was calculated by adding the lake level drop, based on the recession curves, to the observed precipitation for that period. According to maps produced by Bruce and Weisman (1967), this four-month period would account for about 80 percent of the annual evaporation. Therefore, the annual evaporation for each year of record was calculated by dividing the June 1 to October 1 figures by 0.80. The mean value of annual net evaporation was determined to be about 48 cm (19 in). This is not the actual evaporation rate for Pine Lake. Inadequate records of runoff and estimates of seepage out of the lake bottom, groundwater discharge, and near shore transpiration prevent calculation of a meaningful evaporation rate. Bruce and Weisman (1967) constructed lake evaporation maps of Canada, using evaporation pan data and solar radiation measurements. Based on their map, mean annual lake evapora-

TABLE 4.
Summary of streamflow data, Ghostpine Creek near Huxley

Ghostpine Creek near Huxley - Station No. 05CE012
Monthly and Annual Mean Discharges in cubic feet per second for the period of record

YEAR	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV
1967	-	-	0.0	31.6	44.1	15.8	3.5	0.17	0.0	0.34	0.31
1968	-	-	5.9	2.4	1.2	-	-	4.0	2.4	1.0	-
1969	-	-	0.0	137.0	20.5	4.2	5.6	2.7	5.2	7.3	-
MEAN	-	-	2.0	57.0	21.9	10.0	4.6	2.3	2.5	2.9	0.31

LOCATION - Lat 51 53 40 N
Long 113 14 20 W NATURAL

Ghostpine Creek near Huxley - Station No. 05CE012
Drainage Area = 200 Sq Miles
Annual Extremes of Discharge in CFS and Annual Total Discharge in AC-FT for the period of record

YEAR	MAXIMUM INSTANTANEOUS DISCHARGE	MAXIMUM DAILY DISCHARGE	MINIMUM DAILY DISCHARGE	TOTAL DISCHARGE
1967	-	-	-	-
1968	-	31.6 CFS ON AUG 5*	0 CFS ON JUL 18*	-
1969	1110 CFS AT 1820 MST APR 6	-	-	-

* - Extreme recorded for the period of record.

TABLE 5.
Results of recession curve analysis of lake level hydrographs - Pine Lake

Year	Lake Level Drop June 1 - Oct 1 (inches)	Precipitation June 1 - Oct 1 (inches)	Net Evaporation June 1 - Oct 1 (inches)	Net Annual Evaporation
1973	3.12	14.55	17.67	22.09
1974	-	-	-	-
1975	7.32	7.24	14.56	18.20
1976	2.40	10.95	13.35	16.69
1977	2.64	12.44	15.08	18.85

Mean Annual Net Evaporation = 18.96 inches = 48.15cm

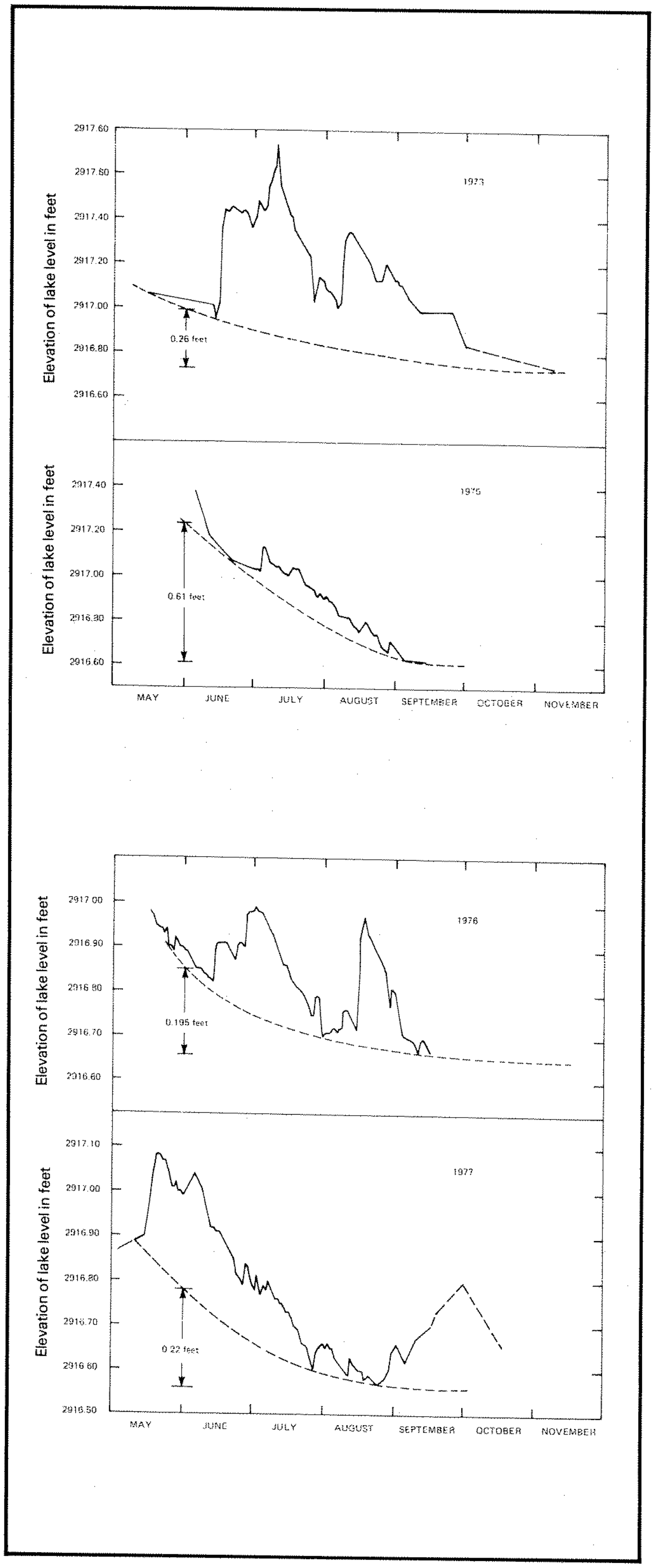

FIGURE 12. Lake level hydrographs, Pine Lake.

tion for the Pine Lake area should be about 74 cm (29 in). Their evaporation estimates, however, apply only to water bodies with small heat storage, such as ponds and shallow lakes, an assumption that may not hold for Pine Lake.

The importance of sloughs to the surface-water hydrology of the Pine Lake area has already been recognized in the earlier discussions of drainage.

The topographic map of the Pine Lake basin does not illustrate the abundance of sloughs in this hummocky area. The aerial photograph in figure 13 better represents their distribution and character.

The presence of sloughs in an area effectively limits surface runoff by acting as small, closed-drainage basins. In effect, they interrupt development of an integrated drainage system, thereby enhancing evaporation, transpiration, or infiltration. Unfortunately, water budget data is not available for the hydrology of sloughs in the Pine Lake area. Freeze (1969b) found that, for a water budget of a parkland region in Saskatchewan, the evaporation rate for sloughs could be assumed to be 80 percent of the annual rate of that for lakes. If this holds true for the Pine Lake area, annual slough evaporation would be estimated at 59 cm (23 in).

Several studies have shown that sloughs significantly affect the local groundwater regime. Sloughs can behave strictly as focal points of groundwater recharge, as groundwater discharge features, or possibly as an intermediate combination of both as a throughflow. In fact, Meyboom (1966b) found an annual sequence of transient flow conditions in Saskatchewan. In short, the surface-water hydrology, groundwater hydrology, and water budget of an individual slough can be complex.

GEOLOGY

GEOLOGICAL SETTING AND REGIONAL STRATIGRAPHY

In south-central Alberta, glacial deposits of the Pleistocene continental glaciation and Recent alluvium form a veneer over bedrock strata of Upper Cretaceous and Tertiary age. Excellent

FIGURE 13. Aerial view of hummocky terrain with sloughs, Pine Lake research basin.

exposures of the bedrock formations are found along sections of the Red Deer River. Underlying these rocks are a thick succession of Lower Cretaceous and Paleozoic strata, many containing commercial quantities of oil and gas. Depth to Precambrian basement is over 3 000 m (10 000 ft). Figure 14 summarizes the regional nature of the bedrock and the deeper stratigraphy in central Alberta.

The Pine Lake basin is characterized by a relatively thin mantle of surficial deposits, usually less than 15 m (50 ft) thick, but locally exceeding 45 m (150 ft). The entire area is underlain by semi-consolidated to consolidated sandstones, siltstones, and shales of the thick Paskapoo Formation, which constitutes the bedrock (Rutherford, 1939; Allan and Sanderson, 1945; Green, 1970). Table 6 is a stratigraphic chart of the formations in the Pine Lake basin, down to and including the Lea Park Formation. Information about the units below the Paskapoo Formation is based on interpretation of geophysical logs from deep oil and gas wildcat wells (fig. 5) and on the compilation by Green (1970). The Paskapoo Formation and glacial drift, which combined exceed 300 m (1000 ft) in thickness, are the focal points for the remainder of this report. In relation to groundwater hydrology, the Paskapoo Formation and drift undoubtedly contain all hydrostratigraphic units that would be of theoretical and practical importance. Furthermore, these shallow rock units are basically the only deposits for which detailed geologic, geophysical, and hydrogeologic data are available.

PASKAPOO FORMATION

Definition and Nomenclature

Allan and Sanderson (1945) made the first extensive study of the Paskapoo rocks in south-central Alberta. They noted that, in general, the Edmonton Rocks are clayey and impervious whereas the Paskapoo rocks absorb surface water readily and, at many locations along the

TABLE 6.
Stratigraphic chart of formations, Pine Lake area

Era	Period	Epoch	Group or Formation		Lithology	Thickness
Cenozoic	Quaternary	Pleistocene	"Glacial Drift"		till; lacustrine sand, silt, and clay; outwash sand and gravel	0 - 50 m (0 - 170 ft)
	Tertiary	Paleocene	Paskapoo Formation		gray, thick-bedded, calcareous cherty sandstone; gray and green siltstone and shale; minor coal and tuff beds	76 - 300 m (250 - 1000 ft)
Mesozoic	Cretaceous	Upper Cretaceous			Scollard Member: feldspathic sandstone and bentonitic shales; thick coal beds (nonmarine)	30 - 75 m (100 - 250 ft)
			Edmonton Group	Battle Formation	purplish-black bentonitic mudstone; siliceous tuff beds	4 - 9 m (15 - 30 ft)
				Whitemud Formation	pale gray-white bentonitic sandstone	4 - 6 m (15 - 20 ft)
				Horseshoe Canyon Formation	gray, feldspathic, clayey sandstones and mudstone; carbonaceous shale; coal and bentonitic beds; minor thin limestones (mainly nonmarine)	400 - 425 m (1300 - 1400 ft)
			Bearpaw Formation		dark gray shale and silty shales; minor sandstones (marine)	30 - 75 m (100 - 250 ft)
			Belly River Formation		gray, thick-bedded, feldspathic sandstones; gray clayey siltstone; gray and green mudstone (nonmarine)	200 - 290 m (650 - 950 ft)
			Lea Park Formation		dark gray shale; pale gray silty shale (marine)	140 - 180 m (450 - 600 ft)

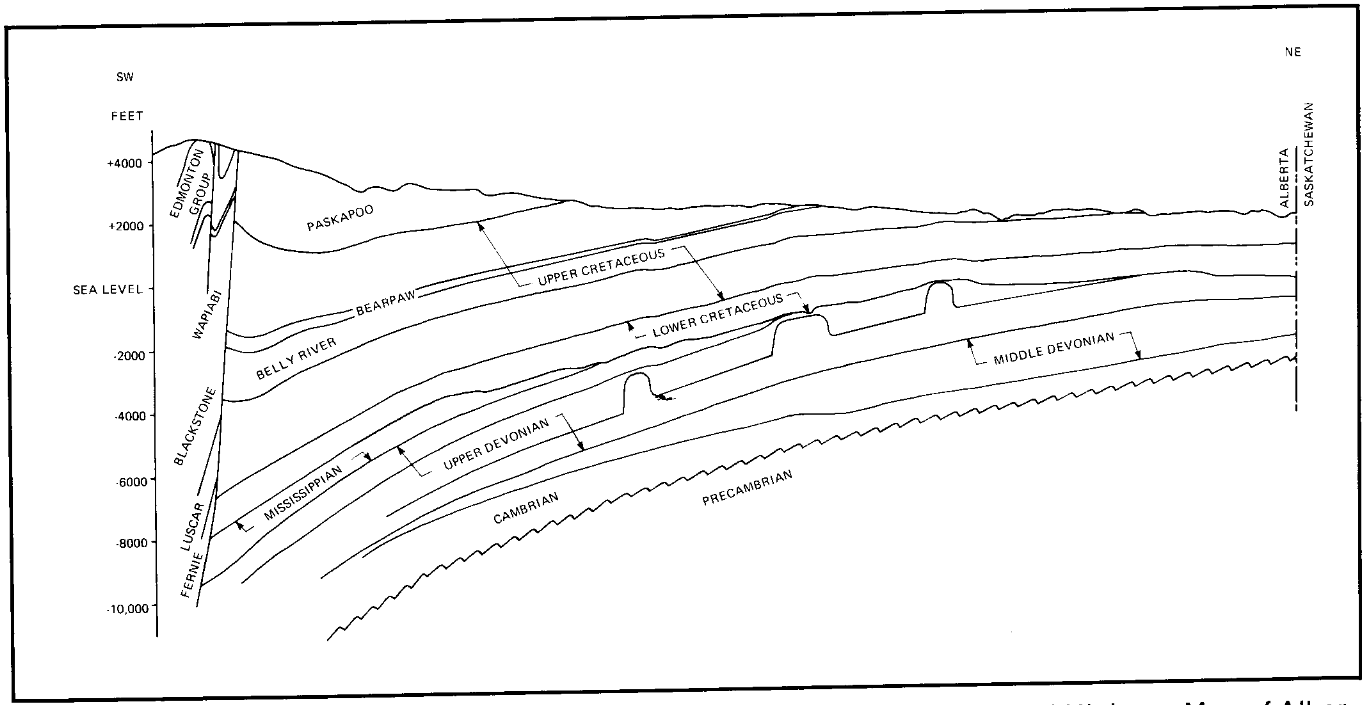

FIGURE 14. Diagrammatic cross section through central Alberta (after Geological Highway Map of Alberta, Canadian Society of Petroleum Geologists 1975). Vertical Exaggeration is 20:1.

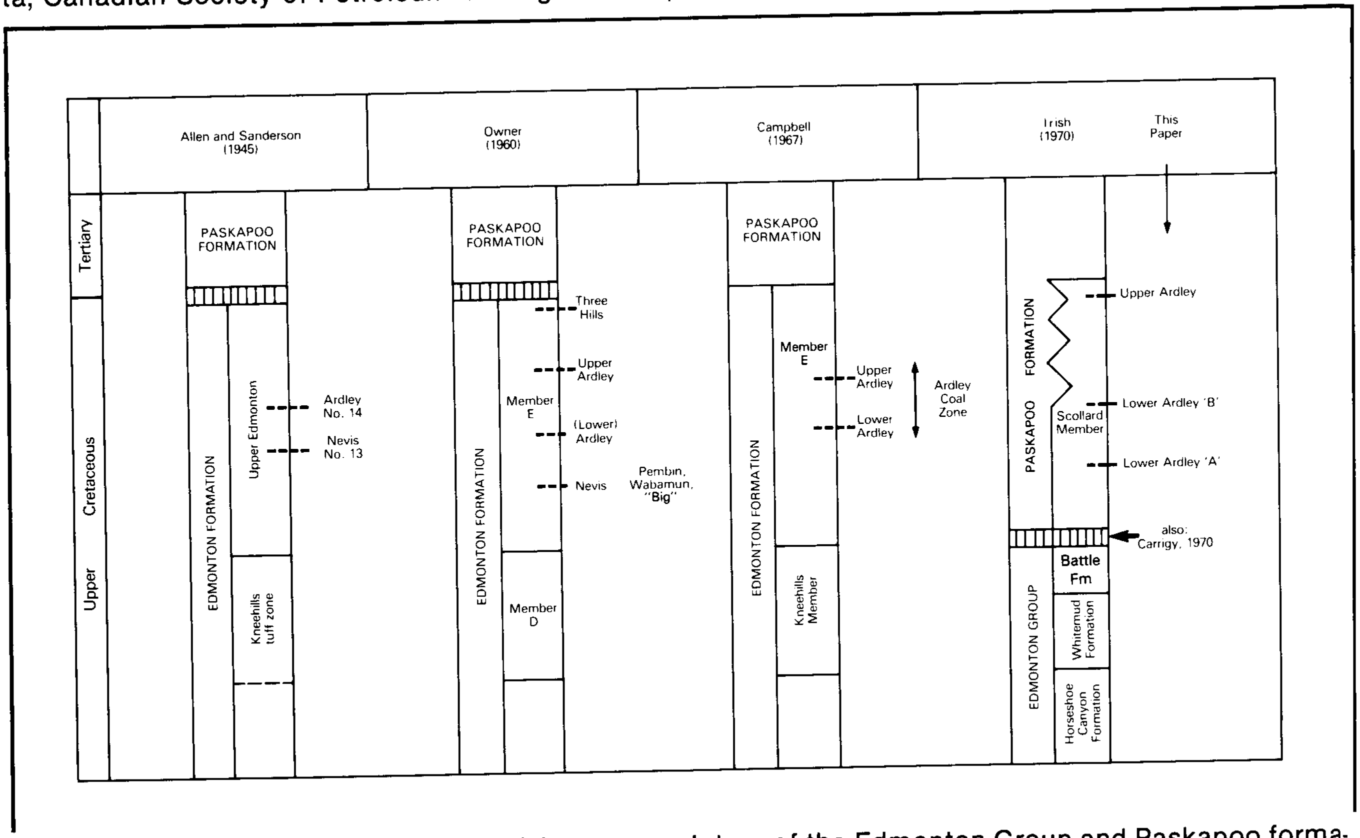

FIGURE 15. Stratigraphic table summarizing nomenclature of the Edmonton Group and Paskapoo formation (after Holter, Yurko, and Chu, 1975).

valley of the Red Deer River, the contact between these two formations is marked by numerous springs. A further contribution by Allan and Sanderson (1945) was the identification of a widespread volcanic ash unit in the upper part of the Edmonton strata, later named the Kneehills tuff.

Since the study of Allan and Sanderson (1945), many geologists have improved upon the stratigraphy of the Edmonton-Paskapoo strata. Ower (1960) devised a detailed division of strata and concluded that the upper boundary of the Edmonton Formation be placed at the first thick sandstone above an extensive coal bed known as the Ardley. Campbell (1967) used Ower's subdivision in his detailed examination of the Ardley coal zone but stressed that the transitional nature of the strata made the Edmonton-Paskapoo boundary arbitrary. Carrigy (1970) proposed that the lower boundary of the Paskapoo Formation should be accepted as the top of the Kneehills tuff unit (Battle Formation) in central Alberta. Irish (1970) concurred with this boundary revision and completely modified the Upper Cretaceous-Tertiary nomenclature of central Alberta. Holter, Yurko, and Chu (1975) contributed further stratigraphic knowledge of the Paskapoo Formation in their study of the Ardley coal zone. They were able to map three main coal units; Lower Ardley 'A', Lower Ardley 'B', and the Upper Ardley. These relationships are summarized in figure 15.

The terminology of Irish (1970), which is currently the most widely accepted, is adhered to in this report. As an example of the nomenclature of Irish (1970), figure 16 shows a representative subsurface section of the Paskapoo Formation in the Pine Lake research basin. The Upper Ardley coal zone appears to be absent or poorly developed over much of the Pine Lake area and, therefore, the Lower Ardley 'B' has been chosen as the marker bed for the top of the Scollard Member.

Lithology

Irish (1970) described the general lithology of that part of the Paskapoo Formation above the Scollard Member as consisting of massive, in part cross-bedded, coarse-grained, buff-weathering, gray calcareous sandstones; well-indurated to soft, fine-grained sandstones and siltstones; and green to gray, friable, silty shales. Although the

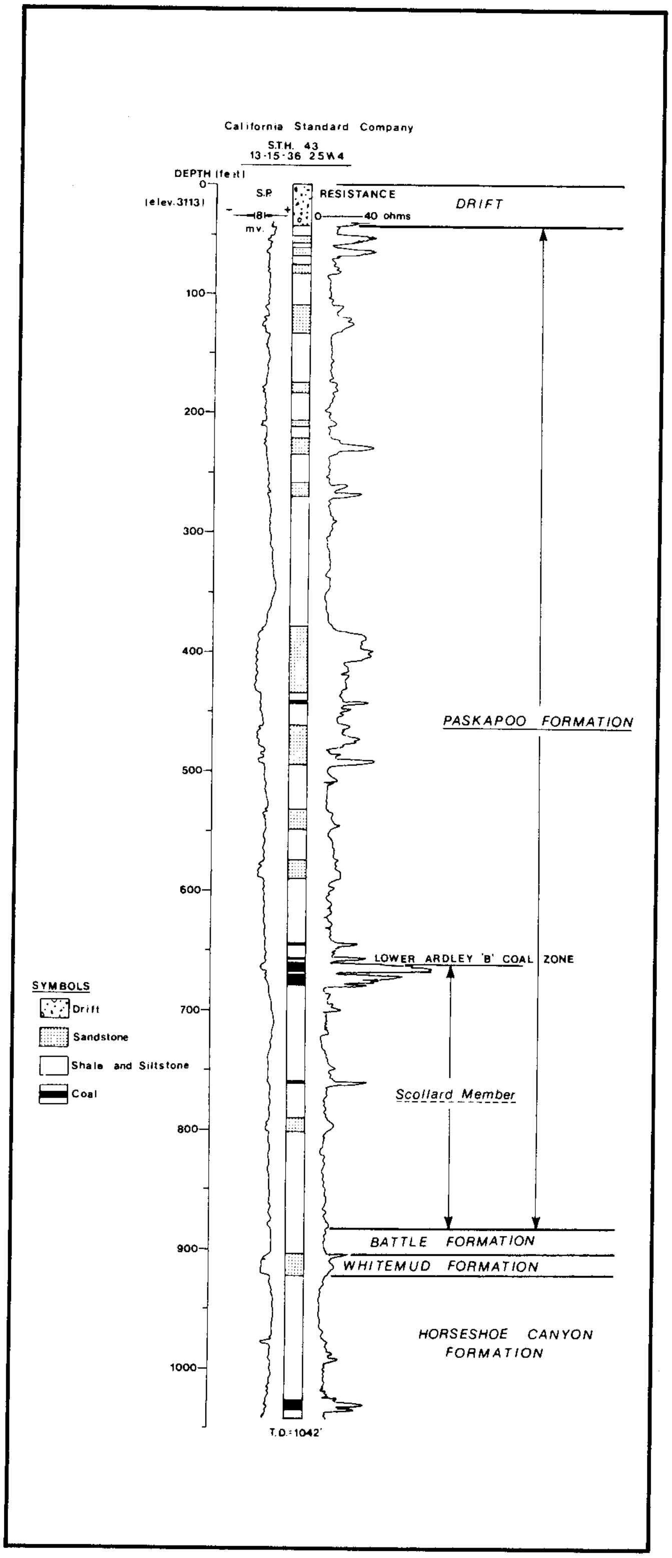

FIGURE 16. Representative subsurface section of the Paskapoo formation in the Pine Lake research basin.

sandstones are dominated by quartz with minor amounts of feldspar, fragments of shale, carbonate, chert, quartzite, and clay pellets comprise an important percentage which typically gives these sands a "salt and pepper" textural appearance (Allan and Sanderson, 1945). Also present in this section of the Paskapoo Formation are thin beds of argillaceous and siliceous, fossiliferous limestone, lenses of pebble conglomerate, thin beds of woody coal, carbonaceous shale, bentonitic clays, and local bands of laminated lacustrine clays.

The Scollard Member is characterized by a lithological succession similar to that described above, except that beds exhibit a greater degree of interlensing and thick, extensive coal seams are prominent. As noted earlier, a maximum of three major coal units (Lower Ardley 'A', Lower Ardley 'B', and Upper Ardley) are discernible in the Scollard Member.

Bedrock exposures (Paskapoo Formation) in the Pine Lake area are relatively scarce (see fig. 4) and appear to have been created by road construction. Thickly bedded to massive sandstones dominate most of these exposures, although bentonitic grayish-brown clays and hard bluish-green, carbonaceous shale were at a road cut near the north end of Pine Lake.

In the subsurface, lithologic logs from water well drillers' reports usually contain descriptions of the Paskapoo Formation as consisting of interbedded gray to green shale, gray sandy shale (siltstones?), and soft gray sandstone. Drillers frequently describe these rocks as bentonitic and when oxidized are commonly listed as yellow to brown shales or sandstones. Thin woody coal seams, highly fractured shales, and very hard sandstone beds are also encountered during water well drilling in the Pine Lake area. The numerous wells in most parts of the basins provide a good account of the lithology down to about 100 m (300 ft) on the ridges and to about 30 m (100 ft) near the valley bottom. Lithological descriptions of the Paskapoo Formation at greater depths is limited to four coal testholes and four groundwater testholes. All of these drill holes penetrate the section of Paskapoo strata above the Lower Ardley 'B' but none were drilled through the entire Scollard Member.

Lithostratigraphy

The nature and distribution of lithostratigraphic units is of primary concern in hydrogeologic investigations because of the influence on the distribution of aquifers. Stratigraphic relationships also impose strong control on the groundwater flow pattern in a sedimentary basin.

As explained earlier, the regional stratigraphy of the Upper Cretaceous-Tertiary strata is based almost entirely on lithologic criteria and areally persistent marker beds such as the Kneehills tuff (Battle Formation) and Ardley coal zone (Scollard Member). For hydrogeologic purposes, a greater degree of refinement is needed. Although abundant lithologic logs are available for the shallow bedrock, subsurface geologic information on deeper sections of the Paskapoo Formation is scarce. Fortunately, an excellent distribution of electric logs (fig. 5) from relatively deep (maximum 380 m) structure testholes exist in the Pine Lake area. These logs consist of a spontaneous-potential and a single-electrode resistance curve, both of which appear to be quite responsive to various lithologies (for example sandstone, shale, coal, and drift). Figure 16 is an example of a structure testhole electric log and the typical log responses. Reliable interpretation of the structure testhole electric logs was made by comparing their responses to the logs of the coal tests.

Several geological sections, based largely on the interpretation of electric logs, were constructed in order to determine the subsurface lithostratigraphy of the Pine Lake research basin. These sections are shown in figures 17 to 23 and their locations are given in figure 5. Because most of the structure testholes and coal testholes rarely penetrated the entire Scollard Member of the Paskapoo Formation, the lithostratigraphy below the Lower Ardley 'B' coal zone has not been illustrated. Several electric logs of the Scollard Member indicate that it is essentially a shale-siltstone unit in the Pine Lake area, although it is not completely devoid of sandstone (fig. 16). Information presented on the cross sections is also supplemented by geologic logs of water wells and a few radioactivity logs of cased oil and gas wells.

The geological sections show three major lithostratigraphic units in the subsurface; glacial drift, sandstones, and mudstones (shales and siltstones). The stratigraphic detail of the glacial drift is not shown on these diagrams because all drift deposits have been lumped as a single lithostratigraphic unit. Only the major units of sandstone have been represented; zones of predominantly sandstone are shown as solid units. Therefore, thin beds of sandstone may be found in those parts of the sections shown as shale and siltstone and vice versa.

The most prominent stratigraphic feature in the geological sections (figs. 17 to 23) is the areally persistent nature of the Lower Ardley 'B' coal zone. This coal is easily detected on electric logs (fig. 16) and characteristically occurs as two major coal beds, which are less than 2 m (6 ft) thick, separated by a shale and bounded at top and bottom by minor coals and shaly coals. A few minor coal seams exist above the Lower Ardley 'B', but their extent in the Pine Lake area is difficult to assess. These thin coals were not correlated because the thick Ardley was more than sufficient for the purposes of this study.

The generalized cross sections illustrate several other important stratigraphic features. Although correlation of sandstone units in the Paskapoo Formation is difficult, the task is not impossible. The Paskapoo Formation is often described as consisting of strata that are irregularly distributed and of a lenticular nature. The geological sections through the research basin appear in part to support this general observation. Nevertheless, correlation of sandstone units over several miles is possible, although the complexity of this task may vary from being rather simple (section A-A*) to quite complicated (section B-B*). Individual sandstone units, which can be mapped over substantial distances, are usually greater than 5 m (15 ft) in thickness and in some areas of the basin many sandstone beds appear to coalesce, forming units of sandstone that are over 100 m (300 ft) thick.

Figure 24 summarizes the areal variation in lithologies over the basin. It is a sandstone percentage map of that part of the Paskapoo Formation above the Lower Ardley 'B' coal zone. A more sophisticated facies map could have been constructed, but hydrogeologically this simple map is sufficient to outline the areal variation in lithology. The Paskapoo Formation in the Pine Lake research basin is a shale-siltstone sequence, particularly in a large area west of Pine Lake where over 80 percent of the strata are mudstones. A prominent northwest-trending sandy lobe extends into the western edge of the basin but quickly dissipates. Sandstone comprises up to 70 percent of the section in the area immediately southeast of the basin, of which a major sandy lobe extends northward forming part of the basin's eastern ridge.

Structure and Thickness

In the subsurface, the Lower Ardley 'B' coal zone is an excellent marker bed for examining the structure of the Paskapoo Formation. Figure 25 shows the elevation on top of the Lower Ardley 'B' coal zone in the Pine Lake research basin. The structure contours largely trend north-south, although perturbations in the contour pattern are readily apparent. One structural trend appears to coincide with the western divide of the basin, while another major undulating trend in the contours sweeps across the basin in the east-west fashion near the north end of Pine Lake. A few isolated and closed structural highs and depressions are also found in the area. Although direct evidence of faulting and folding of Paskapoo strata in the Pine Lake area is not available, the undulating trends on the structure contour map suggest that gentle flexures in the strata probably occur locally. In fact, the geological sections C-D*, D-D*, and E-E* (figs. 19, 20, and 21) appear to illustrate a noticeable (but almost imperceptible) depression of the sandstone units towards the drainage way of the research basin and a gentle rise towards the ridges which form the drainage divides. The Ghostpine Creek drainage basin may therefore represent a broad gentle flexure of the bedrock strata. Allan and Sanderson (1945) recognized the regional nature of this feature and hypothesized that much of the parallelism of stream courses west of the Red Deer River (fig. 2) could be attributed to the direction of folding.

The thickness of the Paskapoo Formation in the Pine Lake basin ranges from about 110 m (350 ft) in the south to over 360 m (1200 ft) in the northern part of the basin. For that part of the stratigraphic sequence above the Lower Ardley 'B' coal, the thickness ranges from around 75 m to 300 m (250 to 1000 ft). The areal variation in thickness of this unit across the research basin is well illustrated by the geological sections.

Bedrock Topography

The upper boundary of the Paskapoo Formation in the Pine Lake area is an erosional surface, uncomformably overlain by glacial deposits of Pleistocene age. Figure 26 is a contour map showing the elevation of the bedrock strata, which in turn represents the preglacial surface topography of the research basin. The main source of data used in constructing this map was the elevation of the glacial drift-bedrock contact in boreholes, supplemented by elevations of bedrock exposures, and interpretation of electric logs.

The most prominent feature of the bedrock topography in the research basin is that it closely reflects the general nature of the present topographic highs. Bedrock valleys are found along existing drainage ways, except where the present terraine is quite hummocky. The contour map (fig. 26) shows that what is now Ghostpine Creek, Pine Lake, and their tributaries was a northwest-trending, relatively deeply incised, southward flowing drainage system. This preglacial bedrock valley is named the Archithinue Valley. The present Ghostpine Creek system has a maximum relief in the research basin from valley bottom to adjacent plateau of about 45 m (150 ft). The Archithinue Valley was a much more deeply incised feature with relief as much as 75 m (250 ft). Ghostpine Creek is an underfit stream meandering in the location of a broad and deep valley bottom which was eroded before the Pleistocene glaciers advanced and is now partly buried by unconsolidated deposits.

GLACIAL DRIFT

Definition and Nomenclature

"Glacial drift" is used here to refer to the unconsolidated Pleistocene deposits of boulders, till, gravel, sand, silt, or clay that were formed as a result of continental glaciations. Although minor amounts of Recent alluvium exist, no deposits of the preglacial Saskatchewan Gravels and Sands (Stalker, 1960), which usually are associated with the preglacial valley of the Red Deer River, are present in the Pine Lake research basin.

Distribution and Lithology of Drift Deposits

The surficial geology of the research basin (fig. 27) is characterized by extensive ground moraine and hummocky moraine. Both of these deposits consist of till or boulder clay which is the most abundant surficial material in the study area. The till is comprised largely of sediments derived from the local bedrock (Paskapoo Formation and Edmonton Group) but also includes rock fragments of igneous and metamorphic origin as well as hard sandstones and carbonates from distant areas. Much of the till in the Pine Lake area is sandy because of the prominence of the Paskapoo Formation. Hummocky moraine, typically thicker than the ground moraine deposits, is found in areas of high elevation and characterized by knob-and-kettle topography. The hummocky moraine also includes numerous pockets and hills of sand and gravel and is associated with short esker ridges, kames, wind gaps, and dead-ice plateaus (fig. 27). Ground moraine was deposited mainly from the base of the glacier as a consistent and even blanket of till. Stalker (1960) describes these till deposits as compact, dense, and very sticky when wet due to the abundance of bentonite derived from the local bedrock. In general, tills have a very low hydraulic conductivity, although it may increase slightly where material is sandy or jointing is common.

Thickness

Figure 28 shows the total undifferentiated thickness of the glacial drift in the Pine Lake research basin. The most conspicuous feature delineated on this isopach map is the thickening of the drift deposits towards the thalweg of the Ghostpine drainage way. Borehole data indicate that the thickness of the drift along this preglacial valley can exceed 45 m (140 ft). Drift deposits are also more than 30 m (100 ft) thick in other parts of the research basin, especially in areas where strongly developed hummocky moraine is dominant (compare figures 27 and 28). The most outstanding example of this feature is found in an area just north of the research basin divide in township 37, range 25. Over 50 m (160 ft) of drift was encountered in two testholes in this area and several others penetrated drift more than 40 m

(130 ft) thick. Contouring drift thickness in these regions is very difficult and probably misleading; for the completeness of the map, however, it has been included in figure 28. In reality, smooth isopach patterns probably do not exist. The character of hummocky moraine is such that drift thickness should be expected to change abruptly and therefore the true situation would be much more erratic than that depicted in figure 28.

Stratigraphy

Figure 29 shows the subsurface geology of the drift deposits as interpreted from drillers' logs of water wells. The detail of the analysis is limited because of the complexity of the geology and quality of data. Two major tills are discernible in the subsurface: a blue till and a gray till. The blue till is widespread in the northern part of the study area and is typically blue-gray, dark blue, or sometimes black, very sticky, and clay-rich relative to the gray till. The dark color imparted to this till is possibly due to a high content of carbonaceous material and length of burial under saturated conditions. This material, however, retains its dark color even when near the surface and in the unsaturated zone. Gray till is the most abundant drift material in the research basin. Drillers often describe these deposits as gray sandy clay till or, if oxidized, as various shades of yellow and brown. Compared to the blue till, the texture of the gray till appears less massive or dense and possibly more permeable. Figure 29 indicates that the blue till is usually a basal unit overlain by gray till (see, for example, well number 160) or by sands and silts (see well number 291). At some locations, however, blue till is also underlain by gray till or sand (see well numbers 338 or 354).

The abundance of outwash and glaciolacustrine sands and silts along the preglacial drainage way is as apparent in figure 29 as on the surficial geology map. Borings made along this thalweg penetrate thick deposits of interbedded gravel, sand, and silt, whereas further away from the drainage way these sediments become integrated with the tills, in places forming an obvious intertill deposit. Significant amounts of stratified drift area also occur near the ridge forming the divide in the southwest part of the research basin. The deposits in this area may in part be associated with ice-contact drift rather than outwash.

HYDROGEOLOGY

Hydrogeology can be defined as the science that deals with the occurrence, distribution, and movement of groundwater, its relation to the subsurface and surface environment, and the nature of groundwater chemistry. Fundamental to this definition are two concepts, the hydrogeologic environment and the groundwater regime. The hydrogeologic environment refers to those aspects of topography, geology, and climate influencing groundwater conditions. Tóth (1970) described the groundwater regime as a number of parameters representing the physical and chemical conditions of groundwater. Thorough study of the groundwater regime would involve investigating the amounts of water present in the saturated zone, pattern of groundwater flow, volume discharge or flow velocity, chemical composition, water temperature, and the variance of these parameters with time. Theoretically, the relationship between the hydrogeologic environment and the groundwater regime is genetic and quantitative and can be mathematically modelled, provided sufficient field information is obtained and the physics of the system understood.

The basic goals of a hydrogeologic investigation of a basin are to determine:

1. the hydrogeological environment;
2. the groundwater flow systems;
3. its interaction with surface hydrology through recharge and discharge;
4. the chemistry of groundwater and its relation to other regime parameters;
5. the quantitative hydrologic properties of subsurface materials with special emphasis on aquifers and the groundwater budget of the basin; and,
6. the groundwater resources in regard to existing demands, potential development, and environmental considerations.

This study so far has dealt with the hydrogeologic environment. The balance of the report will deal with these other aspects of the groundwater study of a basin.

THE ANALYSIS OF GROUNDWATER FLOW

Subsurface flow patterns can be deduced from either theoretical considerations or the analyses of field techniques. The theoretical approach relies on the fact that groundwater flow obeys the laws of physics and, therefore, can be rigorously modelled mathematically, provided boundary conditions and the hydrogeologic environment are known. Field techniques also make use of the hydrogeologic environment in interpreting flow patterns. These techniques may consist of several types of analyses, commonly grouped as follows:

1. piezometric or potentiometric analyses;
2. interpretation of hydrogeochemistry;
3. evaluation of groundwater field phenomena (surficial evidence);
4. determination of groundwater temperature distribution; and,
5. use of environmental isotopes.

The first three methods are used most frequently in regional groundwater flow studies, and are the only ones considered in this analysis.

The theoretical approach to the steady-state analysis of regional groundwater flow was first established in the classic treatise on the theory of groundwater motion by Hubbert (1940). He showed that groundwater flow is governed by a potential field represented by hydraulic head. Tóth (1962, 1963) expanded on Hubbert's work by applying the concept that exact groundwater flow patterns can be obtained mathematically as solutions to formal boundary-value problems. He documented this concept by using analytical methods to solve Laplace's equation for the potential distribution in a two-dimensional model of a small, homogeneous drainage basin. He also developed the concept of groundwater flow systems.

The analytical technique provided by Tóth (1962, 1963) aided in the investigation of the parameters involved in regional groundwater flow. The solutions were limited, however, to specific field conditions with simple basin geometry and geology. This situation was significantly improved with the advent of numerical methods in groundwater hydrology. Freeze and Witherspoon (1966, 1967, 1968) used two and three dimensional finite difference models to simulate groundwater flow in field conditions. These models included anisotropic, heterogeneous groundwater basins with complex water-table configurations. Their study demonstrated how the shape of the water table and underlying hydraulic conductivity contrasts influence the groundwater flow pattern. Figure 30 shows the flexibility of the numerical method. Freeze (1969a) also showed how the theoretical approach can be integrated with field techniques to form a powerful tool for delineating groundwater flow systems.

Research in numerical modelling in the past decade has rapidly advanced the state of theoretical analysis of groundwater flow. Numerous finite difference, finite element, and integrated finite difference models have been designed to treat a broad spectrum of hydrogeologic conditions: steady-state or transient flow, in two or three dimensions and with complex boundary conditions; saturated-unsaturated flow; problems of flow in the

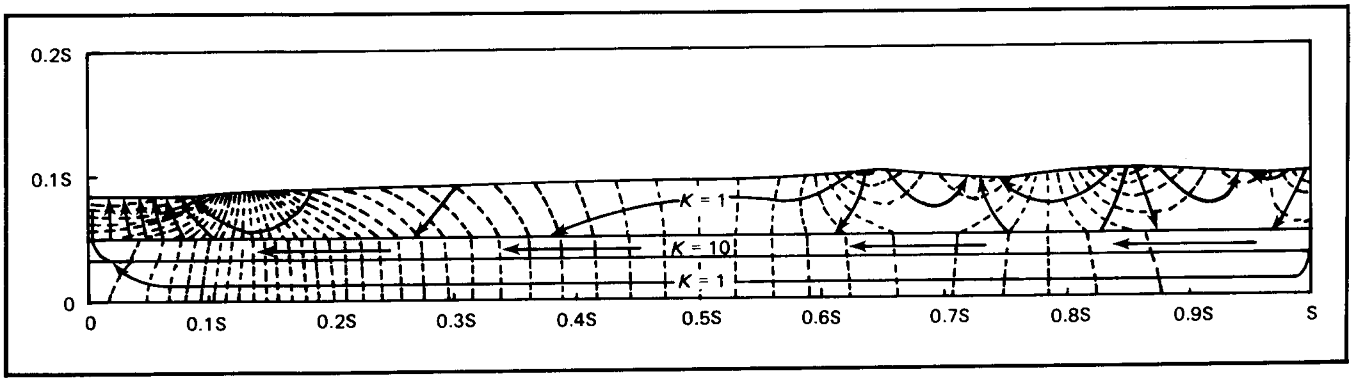

FIGURE 30. Hydrogeologic section showing theoretical flow patterns as determined by finite difference model (after Freeze, 1969c).

presence of free surface and seepage face; mass or solute transport; and flow in fractured rock media.

One recent application of numerical methods by Winter (1976, 1978) is important to the Pine Lake research basin. He employed a finite difference model to simulate in two and three dimensions the steady-state pattern of groundwater flow systems near lakes in a glacial terraine. Boundary conditions in the models were the same as those prescribed by Tóth (1962, 1963) and Freeze (1969a) in their groundwater basin studies. Figure 31 shows one of Winter's hydrologic sections of a multiple-lake system in a homogeneous but anisotropic basin. Based on the potential distributions derived for various hydrologic sections, Winter (1976, 1978) documented the nature of the interaction between lakes and groundwater. He concluded that the continuity of the boundary separating local from regional flow systems determines whether the lake is a recharge, discharge, or throughflow system. Factors affecting this flow system include the height of the water table (relative to the lake level) on the downgradient side of the lake, lake depth, geometry and hydraulic conductivity of aquifers, and the degree of anisotropy.

A detailed theoretical investigation of flow systems in the Pine Lake basin has not yet been attempted. The preliminary results of a simple numerical simulation, however, will be presented later.

WATER-TABLE CONFIGURATION

The water table in the Pine Lake basin is a subdued replica of the topography. Field observations, and reported water levels, indicate depths of less than 5 m (20 ft) below land surface. The water table does not always conform to local topographic relief. The depth and shape of the water table in part reflect subsurface permeabilities in the Pine Lake area.

According to Freeze (1969c), the assumption of a steady-state water table is valid only under certain conditions: that is, if the zone of water-table fluctuation is a very small percentage of the total saturated depth of the basin, and if the configuration of the water table remains in similar form

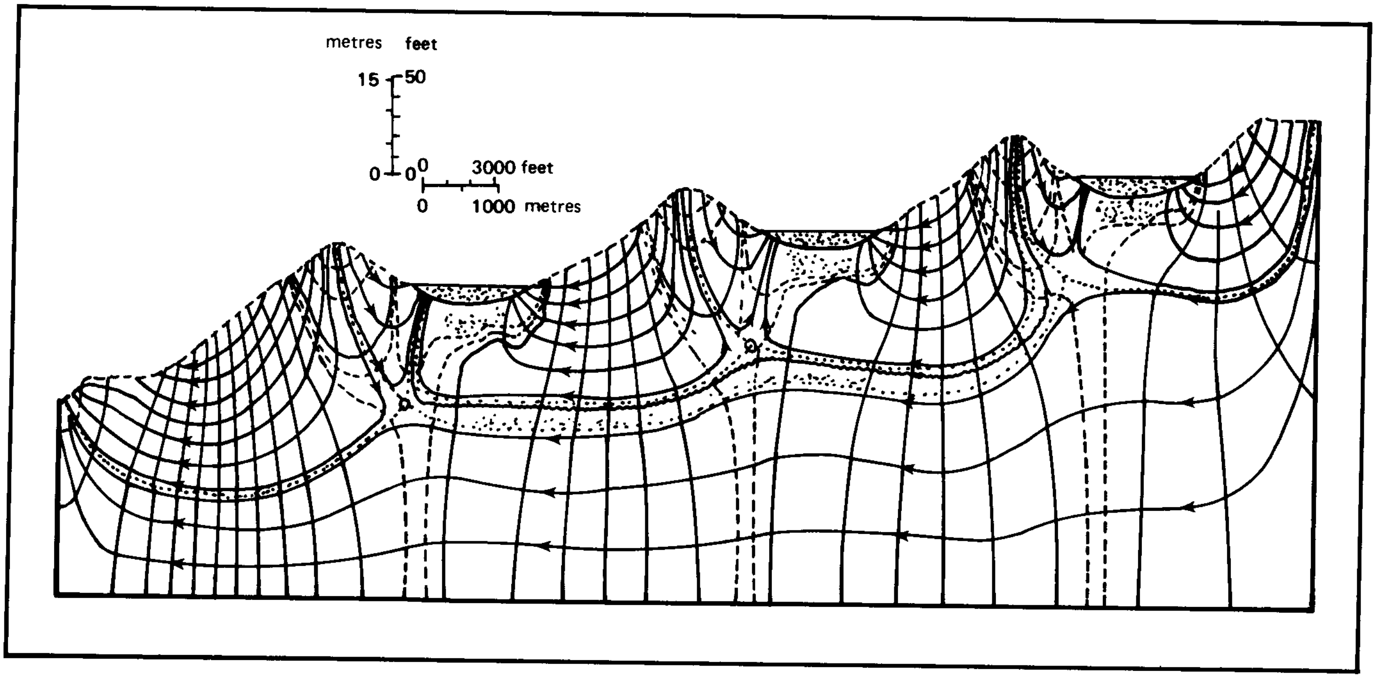

FIGURE 31. Hydrologic section showing groundwater flow pattern near lakes in a multiple-lake system (after Winter, 1976).

throughout the period of fluctuation (locations of recharge and discharge remain the same). These two conditions appear to be met in most parts of the Pine Lake basin, at least on an annual basis. Records of water-table fluctuations over a 15-year period are available for three observation wells in the southwestern part of the basin (fig. 3). The maximum recorded annual water level fluctuations were 64 cm (2.1 ft) for a well completed in a surficial sand, 8.5 cm (0.28 ft) in a well completed in till, and 22.6 cm (0.7 ft) for a bedrock observation well.

The second condition listed above may not be met everywhere in the research basin. For example, Meyboom (1966b) showed that, in areas of hummocky topography, local groundwater flow patterns reversed over the year and therefore demonstrated a transient rather than steady-state character. The importance of this process in the Pine Lake area would have to be determined by detailed field studies.

DISTRIBUTION OF STATIC WATER LEVELS

A piezometric analysis is the most direct method of determining groundwater flow patterns. The static water level for a piezometer open over a small interval represents a discrete measurement of hydraulic head. Water wells may behave in a similar manner if they have been cased down to a specific aquifer where horizontal flow is prominent. When a well has a large open interval, however, the static water level is only a measure of the hydraulic head of the aquifer that has the greatest hydraulic potential in that interval. In an area of upward groundwater flow (a discharge region), the potential increases with depth, so static water levels will be representative of the potential near the bottom of the well, regardless of the length of the open interval. Recharge areas are characterized by a drop in hydraulic head with depth and thus water levels will be under the influence of the shallowest, permeable zone open to the well. In short, knowledge of the general groundwater flow regime and details of well construction are essential to the use of water wells in piezometric analysis.

Unfortunately, the Pine Lake area has no true piezometers from which meaningful hydraulic cross sections could be developed. In addition, the relatively complex stratigraphy and uneven depth distribution of domestic wells in the research basin restrict the use of piezometric surface maps to qualitative investigations. The areal pattern of groundwater flow is illustrated by contouring elevations of non-pumping water levels (fig. 32). This map was constructed from reported static water levels in wells and supplemented from field data on known locations of springs and flowing seismic shot holes. Reference to these data can be found in figure 3 and appendix A.

Figure 32 is neither a piezometric surface map nor a water-table map in that hydraulic heads of different aquifers are present and, at many locations in the basin, hydraulic heads changed with depth. Near the drainage ways and around Pine Lake, static water levels increase with well depth. Exceptions to these trends exist at a few isolated locations. Away from the major ridges and valleys, existing well data suggest that the variation in head with depth tends to be less apparent.

At best, the non-pumping water level map (fig. 32) describes the general direction of groundwater movement. Attempts to derive quantitative information would be pointless. It delineates a groundwater basin where flow is directed from broad recharge areas on the drainage divides and valley flanks to discharge areas near the valley bottom. The greatest proportion of groundwater flux appears to be normal to the drainage way trend. The longitudinal component of flow is relatively small, especially in the basin south of the north end of Pine Lake. Because domestic wells are rarely more than 75 m (250 ft) deep, this water-level map may not represent the flow regime at greater depths.

QUANTITATIVE EVALUATION OF SUBSURFACE HYDROLOGIC PROPERTIES

Rocks of the Paskapoo Formation are typically soft, semi-consolidated lithologies, so porosity is largely primary. The magnitude of effective porosity depends on the degree of cementation and abundance of clay. Secondary porosity exists in the bedrock strata in the form of fractures and joints, which are the result of post-depositional tectonism and possibly glaciation effects. Fracturing is most conspicuous on examining exposures of the Paskapoo Formation and drillers commonly log aquifers as "fractured or broken sandstone" or "fractured shale." A clear relationship between stratigraphy and zones of fracturing is not yet established. Jointing also occurs in the surficial deposits (Stalker, 1960) and undoubtedly influences the permeability of the tills in the research basin. Although quantitative specific yield data do not exist for either the bedrock or surficial deposits, a value of 0.1 is probably reasonable for the bedrock strata and most of the drift, except for the surficial sands and gravels where the specific yield is likely about 0.2.

The drilling of water wells over the past 20 years has produced large amounts of shallow, semiquantitative permeability data. After completing a well, drilling contractors usually conduct a short bail test or pump test to determine well yield. For a domestic well, the period of bailing or pumping is commonly about 30 minutes and the total drawdown is noted. Time-drawdown measurements are rarely taken and observation wells are nonexistent. Occasionally, time-recovery data are recorded and this information has been of value to this study. A few aquifer tests, of several hours duration, also have been performed in the basin. The length of many of these bail or pump tests and accuracy in measurements are probably questionable for proper aquifer testing procedure. All available data, however, were analyzed in order to evaluate the local hydraulic characteristics of the subsurface strata. Measurements of total drawdown (which essentially are specific capacity data) were used to obtain rough estimates of transmissivity through the calculation of "apparent transmissivity" (Farvolden, 1961) which uses the modified nonequilibrium formula (Cooper and Jacob, 1946) and assumes a straight line plot between 0.1 minute and the time of the single observation of total drawdown. The apparent transmissivity either under- or over-estimates the actual transmissivity, depending on whether the drawdown curve flattens or becomes steeper with time. Time-recovery data from bail and pump tests were plotted on semilogarithmic graph paper and transmissivity determined by the straight-line method using the Theis (1935) recovery formula. Time-drawdown data from the longer pump tests were also plotted on semilogarithmic graph paper and the modified nonequilibrium formula (Cooper and Jacob, 1946) was used to calculate transmissivity. Logarithmic plots were made for a few drawdown test data where deviation from the Theis-type curve was evident and in one case where there was data from an observation well. In all, 28 recovery plots and 5 drawdown curves were analyzed.

To present all of the hydraulic test data would be impractical and only three cases will be considered: completion in a sandstone aquifer; a shale aquifer; and a deep well in an interbedded siltstone, shale, and sandstone sequence. The remaining graphs and analyses can be found in appendix D, which also illustrates the hydrogeology of each test location.

Figure 33 shows an example of recovery data from a well completed in a shallow sandstone unit, along the bedrock ridge in the southwestern part of the basin (see fig. 21). Most time-recovery plots (appendix D) show a change in slope during the observations, either as a decrease or as an increase with recovery. These tests were short and may not show whether the changes represent true boundary effects or are a result of well-bore storage. The latest trend of the data was used to determine transmissivity in all tests.

The hydrogeology and results of a 5-hour aquifer test at the north end of Pine Lake are given in figure 34. This well was completed in a shale aquifer that is overlain by clays and sands. In general, the response of the shale is unusual in comparison to tests performed in shale intervals in other parts of the research basin. The reason for this response could be any of the following: fracturing which has greatly enhanced the hydraulic conductivity; induced infiltration with the lake; leakage from the overlying saturated sand layer; or perhaps a combination of the above.

An example of pump test response for a deep well in the extreme northern end of the basin is shown in figure 35. This test was the only one on record where observation well data were also available. Unfortunately, details of well completion were never submitted and drawdown measurements are not of high quality. The drawdown data analyses from the observation well contradict the results of the pumping well. Based on the lithology and results from nearby tests, the transmissivity value determined from the pump-

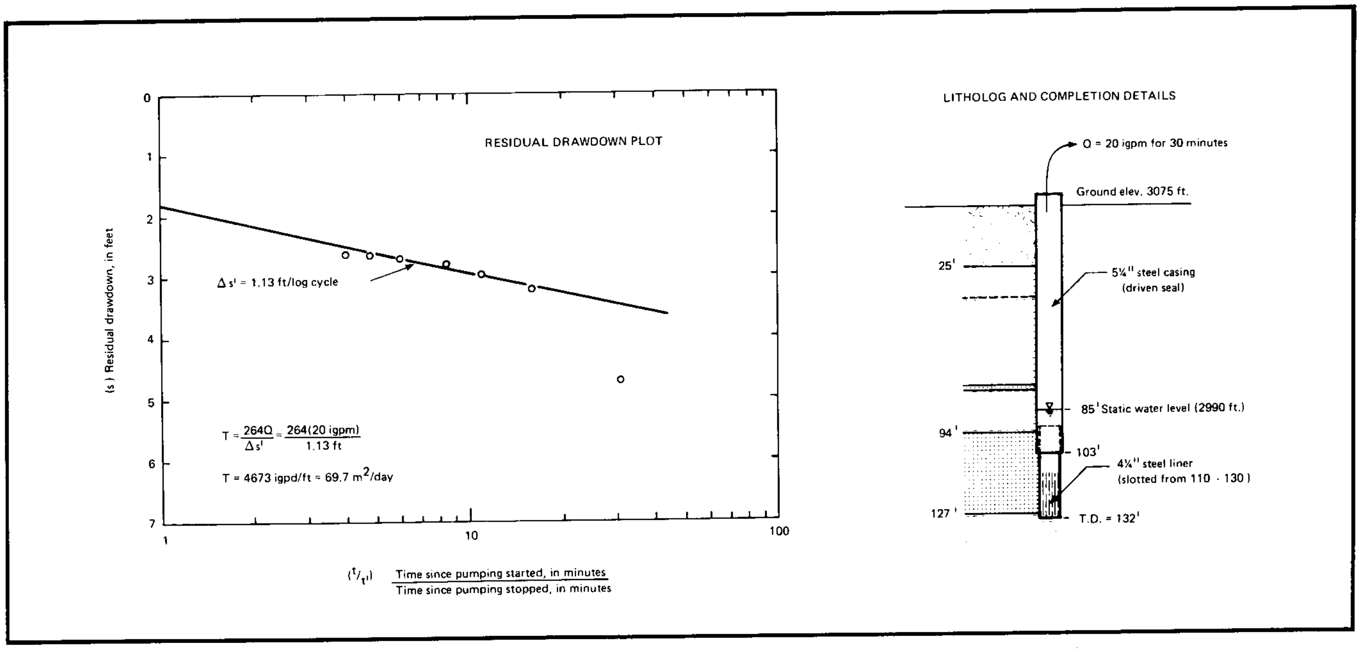

FIGURE 33. Example of time-recovery curve analysis, sandstone aquifer.

ing well data probably does not represent the strata in this area.

Figure 36, a transmissivity map, summarizes the results of evaluating all drawdown and recovery data in the Pine Lake research basin. Only broad regions of similar transmissivity ranges for the shallow bedrock strata are outlined on the map along with the distribution of the various types of data. Variation in well depth, stratigraphy, and distribution of aquifers is responsible for the complexity of the transmissivity pattern. The map does show that regions of high transmissivity appear to dominate the entire eastern divide and a narrow part of the western ridge, probably because of the major shallow sandstone units as shown in figures 18 to 22. Futher interpretation of the hydrogeologic properties of the various lithologies in the Paskapoo Formation requires a closer examination of individual pump test data and local hydrogeology. Hydraulic conductivities were calculated from the transmissivity data and estimated saturated thicknesses of aquifers in the borehole. This information is tabulated in appendix A.

Transmissivities derived from bail or pump tests of sandstone aquifers are commonly in the 30 to 60 m²/day (2000 to 4000 igpd/ft²*) range, although the preliminary data from the ridges in the southern part of the basin indicate that transmissivity can be less than 8 m²/day (500 igpd/ft²). Hydraulic conductivities of sandstone units in the Pine Lake research basin were calculated to be around 0.5 to 25 m/day (10 to 500 igpd/ft²). An average or representative hydraulic conductivity value of these sandstones is probably about 2 m/day (40 igpd/ft²). Higher values may be expected where fracturing is found.

Most wells completed in shale formations are very low producers in the Pine Lake basin, with transmissivities often of less than 1.5 m²/day (100 igpd/ft²), although exceptions are found in competent and fractured shales. Hydraulic conductivity is generally between 0.05 and 0.25 m/day (1 and 5 igpd/ft²) where the shale is soft and therefore tight. Fracturing increases the permeability significantly, so its magnitude can locally exceed those of surrounding sandstones.

Where wells have been completed in a series of strata dominated by siltstone, the yields are intermediate. Transmissivities are generally about 25 m²/day (500 igpd/ft²), although transmissivity could be greater or less depending on the sandstone-shale ratio. On the average, the hydraulic conductivity of siltstones in the

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*imperial gallons per day per square foot

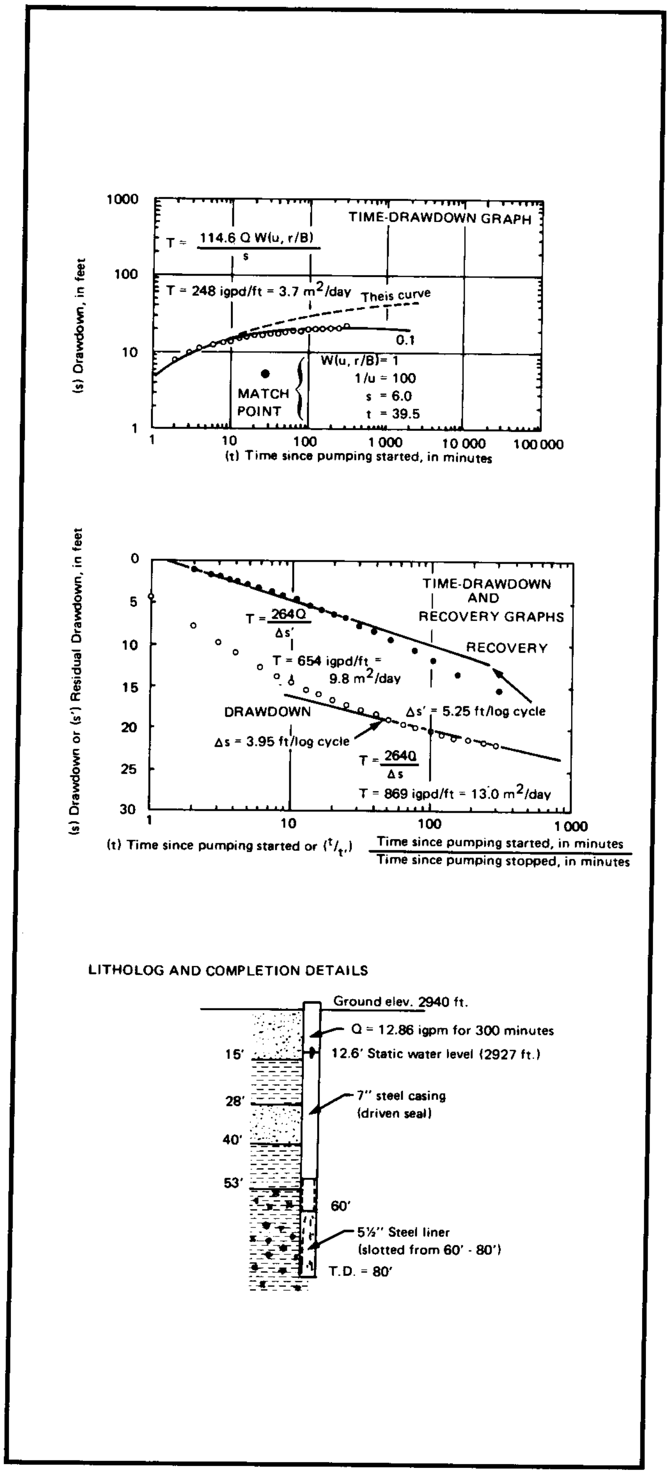

FIGURE 34. Time-drawdown graphs and well completion details of a pump test in a shale aquifer.

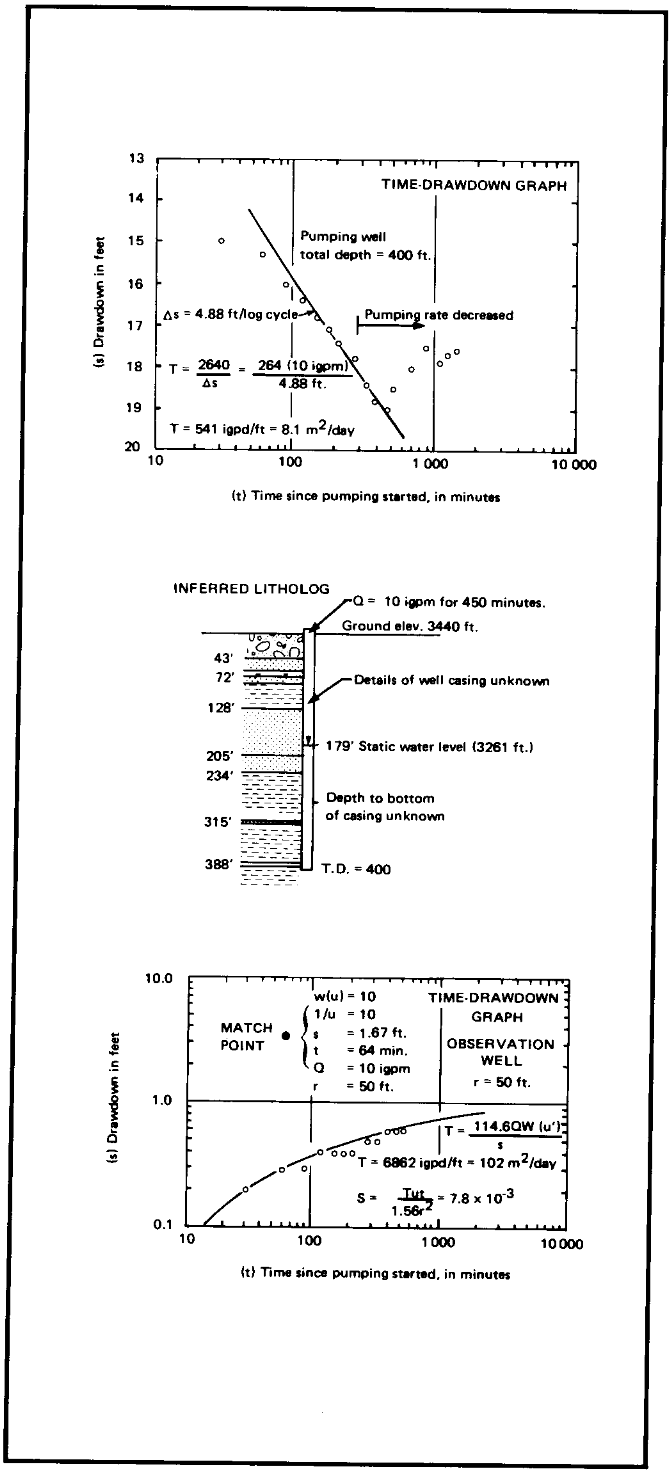

FIGURE 35. Results of a deep well aquifer test in a siltstone-shale-sandstone unit at the northern end of the research basin.

research basin is estimated to be around 0.5 m/day (10 igpd/ft^2).

Modern drilling methods virtually eliminated the need to get shallow water supplies from the glacial drift in the Pine Lake area, so permeability data is nearly absent for this material. Two records of shallow wells near Pine Lake can be used to estimate transmissivity of the outwash deposit in which they are completed. Based on the apparent transmissivity of 120 m^2/day (8100 igpd/ft^2) for a well completed in a 1.2 m (4 ft) thick sand and gravel bed at the north end of Pine Lake, the hydraulic conductivity is estimated to be 100 m/day (2000 igpd/ft^2). Similarly, for a shallow well bottomed in a 1.5 m (5 ft) thick bed of sand and gravel outwash west of the lake, the apparent transmissivity was found to be 13 m^2/day 860 igpd/ft^2 and the hydraulic conductivity is estimated to be about 8 m/day (170 igpd/ft^2). The absence of more accurate data precludes the appraisal of a representative hydraulic conductivity for these deposits. Data for the till deposits does not exist at all. Taking into account its sandy texture and published figures for tills in western Canada, the hydraulic conductivity of till in the Pine Lake area is estimated to be about 10^{-5} to 10^{-2} m/day (10^{-3} to 1.0 igpd/ft^2), depending on the depth and clay content.

The above evaluation of subsurface hydraulic conductivities has not taken into account the possible anisotropy of the bedrock or surficial aquifers. Without suitable quantitative field data, the degree of anisotropy must be estimated from purely geological considerations or published data from areas of a similar hydrogeologic environment. The stratigraphy and sedimentary character of the basin geology is a good indication that the hydraulic conductivity can be expected to be a tensor rather than scalar quantity where the principal directions are oriented parallel and normal to bedding planes. Freeze (1969a, 1969c) used numerical models of numerous field conditions to show that anisotropy is a dominant characteristic of bedrock strata in western Canada. He found that the anisotropy ratio of horizontal to vertical hydraulic conductivity was usually in the order of magnitude of 10 to 100 for hydrogeologic conditions similar to those found in the Pine Lake area. Gabert (1975) applied an anisotropy ratio of 64 in his electric analogue models of the Red Deer area, immediately north of the Pine Lake basin. Based on these considerations, representative figures for the geologic deposits in the research basin appear to be $K_h/K_v = 50$ to 100:1 for the Paskapoo Formation; about 10:1 for till; and perhaps 1:1 for the glacial-lake sands and outwash.

The single aquifer test shown in figure 35 is the only quantitative field data available for evaluating the subsurface storage properties in the Pine Lake area. As shown on the logarithmic graph (figure 35), a storage coefficient of 7.8×10^{-3} was calculated from the data. Most aquifers in the Paskapoo Formation show some degree of confining conditions in that water levels in wells rise under hydrostatic pressure above the water-bearing zone. The hydraulic conductivities of both the bedrock strata and glacial drift are such that the basin's rock framework is a hydraulically interconnected unit. Tóth (1966b, 1968) and Gabert (1975) arrived at similar conclusions from their hydrogeological studies in south-central Alberta. Under these circumstances, aquifers will react in a semiconfined to confined manner when pump tested, depending on the relative hydraulic conductivities. Confined aquifers are found where higher permeability strata are overlain and underlain by rocks of a much lower permeability. Regionally, it is better to adopt the theory of unconfined flow to describe the occurrence of groundwater or better yet discard the terminology of confined and unconfined as suggested by Freeze (1969c). In any event, the storage coefficients of the Paskapoo Formation can be expected to fall in the 10^{-4} to 10^{-2} range. The specific yield of shallow bedrock or drift aquifers likely varies between 0.05 and 0.20.

OCCURRENCE AND DISTRIBUTION OF AQUIFERS

Groundwater flow systems are inherently affected by the distribution of aquifers and the relative hydraulic conductivity contrast with the stratigraphic units. For the various lithologies in the Pine Lake area, the values of hydraulic conductivity listed above basically show which stratigraphic units can be considered the most productive aquifers. For the distribution of these sandstone beds and outwash deposits, see the discussion on geology.

Domestic wells are rarely drilled deeper than 90 m (300 ft) to obtain a suitable supply of groundwater in the Pine Lake area. The most common type of well construction in this region is a small diameter borehole (about 15 cm) which is reamed out to the top of the first significant bedrock aquifer zone, so steel casing can be set with a driven seal. The aquifer interval is usually left as open hole if completed in a competent sandstone, or a torch-slotted liner is installed where caving is encountered (see appendix D for examples). The type and areal distribution of bedrock lithologies, which serve as aquifers to these domestic wells, are shown in figure 37. The term aquifer for the strata in which these wells are completed may be misleading because the water-supply requirement for domestic and stock purposes is usually not greater than 1 m³/day (200 igpd). An obvious feature of the aquifer lithology map is the correlation it has with the distribution of transmissivities. The most productive wells are found in the thicker sandstone units and where bedrock shales are fractured.

Potential sandstone aquifers are well illustrated by the geological sections (fig. 17 to 23). The most extensive proven sandstone aquifer is a shallow unit overlain by siltstone and shale in the western part of the basin, and subcropping below the drift towards the drainage ways. This aquifer is best depicted in section C-C* to F-F* (fig. 19 to 22) where it ranges from about 9 m (30 ft) to over 30 m (100 ft) thick. Unfortunately, permeability data does not exist for many of the deeper, thick sandstones portrayed in the cross-sections. An exception is the very thick sandstone unit as shown in section G-G* (fig. 23). Gabert (1975) bail tested a similar, thick sandstone unit about 8 km (5 mi) northwest of the research basin and evaluated its transmissivity to be around 6 m²/day (4000 igpd/ft²) and the hydraulic conductivity of the water-bearing zones to be equal to 0.3 m/day (6 igpd/ft²). Although this sandstone is stratigraphically equivalent to the unit present in the research basin, its permeability may be different.

On first appearance, the distribution of fracturing (fig. 37) seems to have no definable pattern. Nevertheless, comparing this map with the bedrock topography (fig. 26) shows a number of fractured strata locations along or near the preglacial drainage way. Tóth (1966b) observed the same phenomena in the Olds area of south-central Alberta (Figure 2) and concluded that these fractured zones could be associated with landslides that took place along bedrock channels in preglacial times. In the presence of badland topography, the soft and bentonitic rock types of the Paskapoo Formation would likely be quite prone to sliding near steep valley slopes. Fracturing, present near the drainage divides of the research basin, could be associated with broad, regional folding. Another type of potential fractured aquifer in the Paskapoo Formation are coal seams. According to Vogwill (1979), the hydraulic conductivity of these beds can be quite high, provided the seams are at a depth of less than 45 m (150 ft). Several thin shaly coals are found in the shallow bedrock in the research basin, especially in the shaly sequence around Pine Lake. These thin beds do not constitute significant water-bearing zones.

Most water wells in the Pine Lake area are completed in bedrock in spite of the fact that aquifers exist in the glacial drift. The reasons for this choice are preferences in water quality and ease of well construction. Wells that are completed in the drift are confined to those areas of hummocky moraine and outwash deposits. Adequate supplies of groundwater can be obtained from the till deposits, provided pockets of sand or gravel are present or a permeable avenue exists at the till-bedrock contact. The sands and gravels of the outwash deposits comprise the most promising area for aquifer exploration in the drift.

HYDROSTRATIGRAPHIC UNITS

Maxey (1964) defined hydrostratigraphic units as "bodies of rock with considerable lateral extent that compose a geologic framework for a reasonably distinct hydrologic system." In order to quantitatively identify hydrostratigraphic units in a geologic environment, such as that found in the Pine Lake basin, a substantial vertical distribution of piezometer and hydraulic conductivity data are required. Except for the "shallow" bedrock strata, little information is available for much of the deeper portions of the research basin's geologic framework. In view of this situation, a qualitative appraisal of hydrostratigraphy is the best that can be currently achieved. Based on the available hydrogeologic data and understanding of the lithostratigraphy, four major hydrostratigraphic units can be delineated in the Pine Lake research basin. This preliminary assessment will probably be confirmed, discounted, or modified by future hydrogeologic studies.

Hydrostratigraphic unit 1 is assigned to comprise all of the glacial drift deposits because till deposits have significantly different hydraulic properties from the underlying bedrock. This unit has a great control on the unsaturated flow regime and, therefore, rates of recharge to the saturated zone. Furthermore, the groundwater in this unit often has a unique hydrochemistry.

The second unit, hydrostratigraphic unit 2, includes that part of the Paskapoo Formation in which completion of domestic water wells is economical. The thickness of this unit is therefore governed by the maximum likely depth of a domestic well in any given area. On the main ridges, this could range from 90 to 150 m (300 to 500 ft), whereas near the valley bottom it could be less than 60 m (200 ft). Hydrostratigraphic unit 2 is characterized by highly permeable, lenticular and extensive sandstones alternating with lower permeability shales and siltstones. A major sandstone aquifer is found in this unit over most of the research basin. In the longitudinal geological section G-G* (fig. 23), the base of hydrostratigraphic unit 2 could be placed near the top of the deep thick sandstone in the northern part of the basin and the boundary continued south in a manner that splits the massive sandstone in the extreme south end of the basin. This division would be at an arbitrary depth, perhaps 30 m (100 ft) above the Lower Ardley 'B' coal zone (fig. 23).

The two deepest hydrostratigraphic units are for the most part of a conjectural nature. Unit 3 includes that portion of the stratigraphic sequence between the base of the Lower Ardley 'B' coal zone and lower boundary of hydrostratigraphic unit 2. This unit is characterized throughout the basin by its thick extensive sandstones that dominate the strata, with the exception of the area around Pine Lake where it appears to be replaced by a shaly sequence (fig. 20). The hydraulic conductivity of these sandstones may be as great as the shallower beds in unit 2 but their depth usually preclude domestic well development. An exception to this is shown in figure 22. The occurrence and relative depth of this unit is most favorable to the presence of intermediate to regional groundwater flow systems. Water quality, therefore, may be poorer within hydrostratigraphic unit 3.

The deepest unit, hydrostratigraphic unit 4, comprises all rocks below the Lower Ardley 'B' coal zone. This distinction is based entirely on lithological criteria interpreted from electric logs in the study area. The relative absence of sandstone bodies in the Scollard Member (fig. 16) and deeper formations implies that a major regional permeability contrast probably exists between unit 4 and the shallower hydrostratigraphic units. Gabert (1975) and Ceroici (1979) also differentiated a similar hydrostratigraphic boundary, but on the basis of quantitative hydrologic data.

SURFICIAL EVIDENCE OF GROUNDWATER FLOW PATTERNS

Field mapping of groundwater-generated flow phenomena can be an important method of reconstructing groundwater flow patterns, either in conjunction with measured hydraulic head values or especially in regions where insufficient well data are available. Depending on the local environmental conditions, groundwater flow patterns may be outlined by various physiographic and geologic phenomena which Meyboom (1966a) termed groundwater outcrops. Recharge areas are found to be characterized by a decrease of hydraulic head with depth, topographically elevated areas, abundant dry depressions, relatively thick unsaturated zone, fluctuating water table, well drained soils, variable and lower groundwater temperature, and low total dissolved solids. Groundwater discharge areas are characterized by an increase in hydraulic head with depth, topographically low, general net moisture excess and abundant wet depressions, shallow water table with less fluctuation, flowing wells, springs and seepages, "soap holes", "burnt-crops", abundant growths of phreatophytes, saline soils and salt precipitates, generally warmer and less variable groundwater temperatures, and higher total dissolved solids.

The distribution of flowing domestic wells and reported flowing seismic shotholes (fig. 3 and 4) are noticeably restricted to the valley bottoms in the Pine Lake basin. Most wells are usually less than 15 m (50 ft) into the bedrock where sandstone and shale aquifers are confined locally by clayey tills. Such is the case for many of the flowing wells drilled near Pine Lake (fig. 4). Buried sand and gravels in outwash deposits will also produce flowing wells along the drainage ways where they are locally confined by clays. Both the increasing hydraulic head with depth environment and locally confining conditions are probably responsible for flowing wells. Free-flowing yields are usually less than 0.2 L/s (3 igpm), but they can exceed 3.8 L/s (50 igpm), as at the north end of Pine Lake where shallow sandstones and fractured shales are confined by clays in the glacial drift.

Springs and seepages are quite numerous in the Pine Lake research basin. Rarely does the flow of these springs exceed 0.8 to 1.2 L/s (10 to 15 igpm). An exception to this was found in the sinuous, narrow valley north of Pine Lake (location 11-3, fig. 4) where the flow rate was estimated around 2.7 L/s (35 igpm). Most springs in the basin discharge at rates between 0.1 to 0.4 L/s (1 to 5 igpm). The geologic nature of these features is often difficult to ascertain because vegetation and the glacial drift obscure the situation. Many of these springs have been dug out and cribbed off. The broad areas of seepage along drainage bottoms and springs found along slopes of hills probably indicate upward-rising groundwater flow and shallow water-table conditions in rather homogeneous, low permeability geologic materials. Some larger springs are usually found in valley bottoms near the base of a steep slope. These springs are almost entirely of the contact type, either as a result of permeable sandstone overlying a shale sequence in areas of thin drift or where coarse outwash deposits overlie clayey till. Many springs are further localized by slumping of surficial materials along steep valley walls. At several of the bigger spring locations, "springy," mound-type features are common, although they are not quite the same as the "soap holes" or "mud springs" described by Tóth (1966a).

The saline soil association along the Ghostpine Creek drainage system (Bowers, Peters, and Newton, 1951) was verified by observations of salt precipitates in this area. According to Tóth (1966a), these salt precipitates consist of sodium sulfate, calcium and magnesium sulfates, and sodium bicarbonates in varying amounts. The salts, in association with springs, flowing wells, saline sloughs, and a shallow water table confirm the result of the evaporation of upward-rising groundwater. The microclimate and abundance of surface water in the northern part of the research basin appears to exclude the development of salt precipitates in discharge areas of this region.

Figure 38 summarizes the results of the field observations and their interpretation in the context of regional groundwater flow and shows that Pine Lake, Ghostpine Creek, and their associated tributaries are major discharge areas for groundwater flow in the Pine Lake research basin.

CONCEPTUAL MODEL OF GROUNDWATER FLOW

On the basis of the available geologic data, nonpumping water levels, subsurface hydrologic properties, field evidence of groundwater discharge, and theoretical considerations, it is not a difficult task to formally conceptualize the groundwater flow patterns in the Pine Lake research basin. The groundwater regime in the Pine Lake area is characterized by a three-dimensional, heterogeneous, anisotropic unit or groundwater basin, as in the context defined by Freeze and Witherspoon (1967). A suitable two-dimensional section through a groundwater basin is representative of the flow patterns, provided it is taken parallel to the direction of maximum hydraulic gradient. In the case of the Pine Lake area, a representative section could include any line transverse to the major drainage ways, assuming that the component of regional groundwater flow longitudinal to the basin is negligible in comparison to the lateral component.

The general pattern of groundwater flow (fig. 39) appears to be fairly simple. Groundwater recharge is most pronounced along the main ridges where the flow is essentially vertical through low permeability glacial drift and siltstone-shale strata. Relatively thin sandstones of greater hydraulic conductivity interrupt the vertical flow regime and serve to transmit the water horizontally to areas of local and intermediate groundwater discharge. A number of local flow systems are found, especially where the water table configuration is irregular as in the hummocky terrain on the west side of the basin. Flowlines are refracted substantially on encountering the extensive, shallow sandstone unit in hydrostratigraphic unit 2. This sandstone unit plays an important role in an intermediate-type flow system that together with the local flow systems is responsible for much of the groundwater discharge in the Pine Lake basin. Regional groundwater flow continues downward to the deep, thick sandstone sequence in hydrostratigraphic unit 3. From here, groundwater movement is lateral through the thick sandstones which transmit water from the regional recharge areas in the uplands to the major discharge areas around Pine Lake. Below hydrostratigraphic unit 3, groundwater flow is dominated by a west to east motion that is part of a much larger regional flow system (in the thick Horseshoe Canyon Formation) discharging towards the Red Deer River.

Two features of the groundwater flow patterns cannot be adequately illustrated by the scale of figure 39. One of these is the local pattern of flow associated with Pine Lake. Regionally, it appears to act as a major discharge feature, but locally the situation may be more complex. Although the models of Winter (1976, 1978) do not seem to apply in the regional pattern, they may offer insight into local groundwater flow-lake interaction. A second area where the flow pattern is not properly represented by the regional model (fig. 39) is in the areas of hummocky moraine. This feature is also likely to be complicated by local flow systems. The diagram of Winter (1976) in figure 31 probably represents the type of flow patterns existing in the knob-kettle topography prominent in the northern and western parts of the research basin. Highly developed local systems between sloughs are an integral part of an intermediate and regional system. Even this picture might be over-simplified by the fact that Meyboom (1966b) documented a sequence of transient flow conditions where directions of groundwater flow reversed on an annual basis.

QUANTITATIVE MODEL OF GROUNDWATER FLOW

Finite-difference and finite-element programs were used to obtain quantitative models of the groundwater flow pattern in the Pine Lake basin. Numerical methods are well documented in the hydrologic literature and therefore the theory behind them will not be presented. Remson, Hornberger, and Molz (1971) present an introductory treatment of these subjects, and Pinder and Gray (1977) offer a more advanced dissertation.

For the purpose of this preliminary study, only a very simple analysis was undertaken. The governing equation of groundwater flow for heterogeneous - anisotropic media and steady-state flow is given by

$$\nabla \cdot (K \nabla h) = 0 \qquad (1)$$

where h is the hydraulic head and **K** is the hydraulic conductivity tensor, which in two dimensions is written as

$$K = \begin{bmatrix} Kxx & Kxz \\ Kzx & Kzz \end{bmatrix}$$

Equation (1) is solved numerically for the hydraulic head and these data can be contoured by the computer to produce a quantitative flow net.

Figure 40 shows an example of a finite element simulation along cross section C-C*. Making the hydraulic conductivity of the sandstone units forty times greater than the conductivity of the mudstones and using an anisotropy ratio of 44:1 produced the best qualitative fit with the conceptual field model. Note should be made that the results shown in figure 40 have been plotted as a transformed section in order to properly account for anisotropy (Freeze and Cherry, 1979). Many more simulations of this type and piezometric data will be needed to justify the validity of this model. For now, it should be viewed as a starting point for future numerical studies of the Pine Lake basin.

HYDROGEOCHEMISTRY

Over 200 chemical analyses of well waters, springs, and surface water in the Pine Lake area were examined. Approximately half were preexisting records of samples submitted to local health authorities by private well owners over the past 20 years. The units of measurement for these

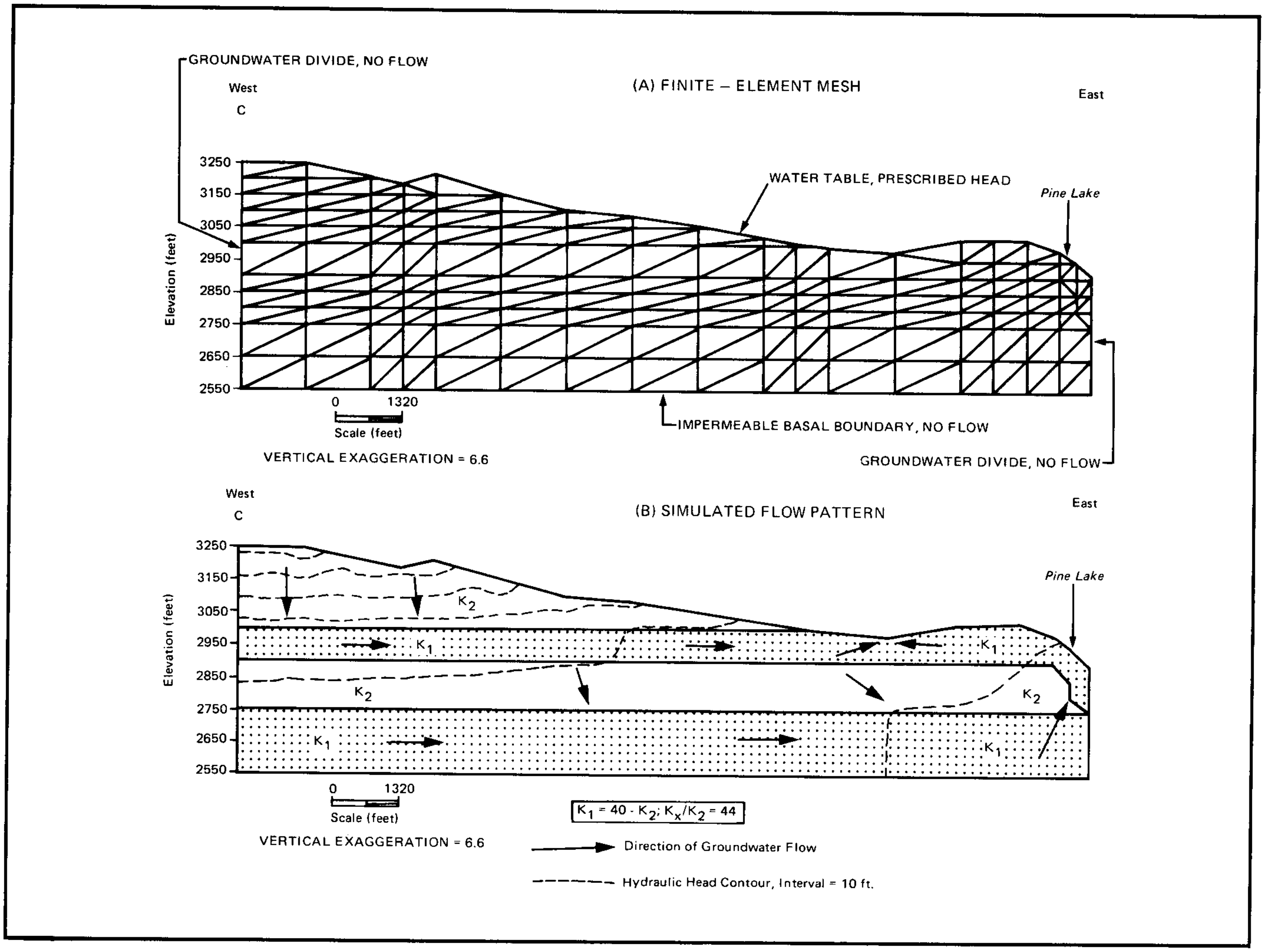

FIGURE 40. Finite element simulation along cross section C-C*, Pine Lake research basin.

analyses are usually parts per million (ppm) or milligrams per litre (mg/L), with grains per gallon used in some older records. Appendix B gives the conversion of this data to equivalents per million (epm) and their respective percentages. The other half of the hydrochemistry data were detailed analyses of water samples from a field survey. These samples were analyzed by the Alberta Research Council Geochemistry Laboratory. The results are also presented in appendix B. Interpreting groundwater chemistry from many of the well samples tabulated in appendix B must be done carefully. In many cases, construction details are unreported and the sampling procedures used by private well owners is often questionable. Nevertheless, for this study, the volume of data and its consistency is sufficient to make general observations on the hydrochemical patterns inferred from the available data distribution (figs. 3 and 4).

CHEMICAL TYPE OR FACIES OF GROUNDWATER

Figures 41 and 42 (trilinear plots of the type proposed by Piper, 1944), show the hydrochemistry of water wells, springs, and a few surface bodies in the Pine Lake area. Because only a few wells in the entire basin are known to be completed in the glacial drift, a Piper diagram for drift wells was not constructed. It is hoped

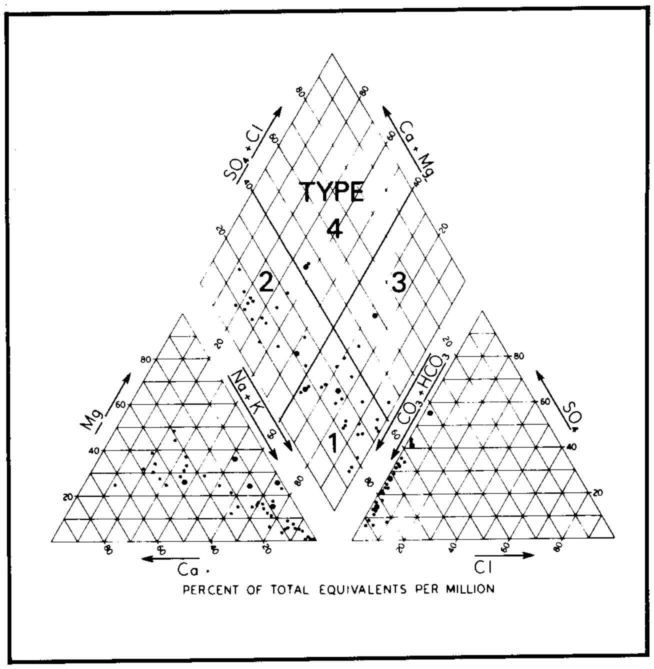

FIGURE 41. Piper trilinear diagram of spring and surface water samples, Pine Lake research basin.

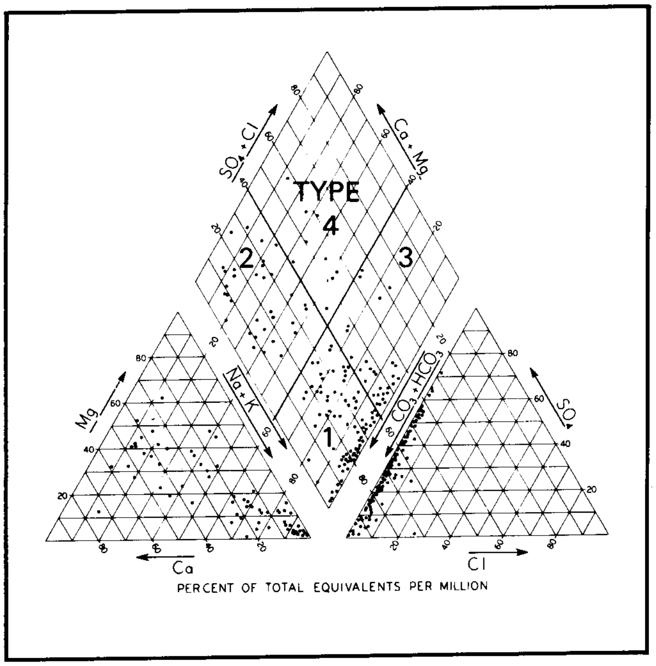

FIGURE 42. Piper trilinear diagram of groundwater samples from water wells, Pine Lake research basin.

that any unique chemistry of groundwater in the drift will be reflected by the analyses of spring waters.

The concept of hydrochemical facies or types introduced by Back (1966) provides an efficient method of evaluating the relationships between groundwater chemistry and those factors that control its character (geology, topography, climate, and groundwater flow). The chemical facies of waters in the Pine Lake basin have been classified on the trilinear plots according to the dominant cations and anions in the water. Boundaries have been arbitrarily chosen at the 60 percent value of equivalents per million for $Na^+ + K^+$ and $HCO_3 + CO_3^{2-}$. Four types of groundwater have been delineated and are numbered on the diagrams in order of their apparent abundance of occurrence. Type 1 is defined as a sodium-bicarbonate facies, Type 2 as a calcium-magnesium-bicarbonate water, Type 3 as a sodium-sulfate-bicarbonate water, and Type 4 as a calcium-magnesium-sulfate-bicarbonate facies. This classification is consistent with that of Gabert (1975), who used over 400 analyses in determining the hydrochemical facies of a large region north of the research basin.

DISTRIBUTION OF HYDROCHEMICAL FACIES

Figure 43 shows the areal distribution of hydrochemical facies in the research basin according to the classification above. Both spring and well data are plotted on this map for a composite representation of the chemistry of groundwater in the shallow bedrock and drift. Hydrochemical cross sections have not been constructed because of the insufficient vertical distribution of data.

As shown on the facies map (fig. 43), type 1 (sodium-bicarbonate) groundwater is the most common hydrochemical facies encountered in the Pine Lake research basin. Its broad distribution does not appear to be topographically controlled nor is it unique to springs or wells. One significant observation is that it is almost always the type of water encountered in deep aquifers.

Type 2 (calcium-magesium-bicarbonate) waters are the next most abundant in the basin. They are most conspicuous in a region enveloping the east side of Pine Lake and extending southeasterly along the flank of the eastern drainage divide. The type 2 facies is also prominent as discontinuous patches near type 3 waters along both drainage divides. No correlation can be made with topography and the occurrence of this facies. Type 2 groundwater is probably a shallow phenomenon because calcium-magnesium-bicarbonate types are frequently found in springs, and wells producing this water are usually less than 30 m (100 ft) deep.

Water dominated by sodium-sulfate-bicarbonate (type 3) is found in an area adjacent to the entire eastern drainage divide and in an irregularly shaped region in the southwestern part of the basin. A few isolated occurrences are found near Pine Lake and Ghostpine Creek; and only one spring in the basin contained a type 3 facies. The majority of wells completed in this facies are between the depths of 30 to 65 m (100 to 215 ft), although about 25 percent of the total are less than 30 m (100 ft) deep.

Type 4 (calcium-magnesium-sulfate-bicarbonate) is the least common hydrochemical facies and is restricted to the major bedrock ridges in the extreme southern part of the research basin. Two isolated sample points are present on elevated ridges in the western part of the study area. Wells in this facies range from around 35 to 80 m (120 to 270 ft) deep. One analysis of a spring (fig. 41) near the edge of a steep bedrock ridge also yielded a type 4 water. A significant characteristic of type 4 waters is that total dissolved solids is always greater than 1000 mg/L (appendix B).

Surface water was not systematically sampled in the Pine Lake basin. The chemistry of the few surface water samples is shown in figure 41, where the appropriate hydrochemical facies is also indicated. Water from the lower reaches of Ghostpine Creek is of the type 1 facies group. In these analyses, TDS range from 500 to 700 mg/L. In comparison, values of 475 mg/L and 500 mg/L were estimated for the TDS content of Pine Lake and the upper reach of Ghostpine Creek, respectively. Analyses of three sloughs in the southern area of the basin were plotted in separate facies, yielding TDS values varying from less than 500 mg/L to over 2500 mg/L.

DISTRIBUTION OF CHEMICAL CONSTITUENTS

In an attempt to further evaluate the hydrogeochemistry in the Pine Lake area, contour maps of various chemical constituents were prepared. These maps, however, showed very little new information over the hydrochemical facies map or correlation with the inferred groundwater flow patterns. For practical purposes, only the distribution of TDS will be described. The spatial variation in TDS is illustrated in figure 44 by a contour interval equal to 500 mg/L. Groundwater in the Pine Lake basin has a dissolved solids value of 1000 mg/L or less. It rarely exceeds 2000 mg/L in the shallow hydrostratigraphic units. The most significant hydrochemical trend displayed by this map is that mineralization of groundwater is highest along the drainage divides and lowest towards lower elevations. The freshest subsurface water (less than 500 mg/L) is found in a region enveloping Pine Lake. Water with concentrations greater than 1000 mg/L dominate the entire eastern ridge, the highly elevated northern upland, and a broad mid-slope region that extends from the southwestern shore of Pine Lake to the southern edge of the basin in Township 35, Range 24. Except for a few isolated areas, most of the western drainage ridge is relatively low in TDS in comparison to its eastern counterpart. Anomalously high TDS concentrations (greater than 2000 mg/L are found in an area of hummocky moraine in the northeastern part of the basin and on a bedrock ridge at the southern extremity. Neither of these high TDS wells is very deep; both are less than 60 m (200 ft).

INTERPRETATION OF HYDROCHEMISTRY

A lot of research has been devoted to the use of the chemical composition of groundwater as an interpretive tool in hydrogeological studies. Various authors laid the foundation of this theory. They sought to show how groundwater chemical types could be attributed to groundwater flow and the hydrogeologic environment. For example, according to the theory of Chebotarev (1955), one should see the following regional changes in dominant anions with distance and age:

$$HCO_3^- \rightarrow (HCO_3 + SO_4^{2-}) \rightarrow (SO_4^{2-} + Cl^-) \rightarrow Cl^- \quad (2)$$

This sequence implies groundwater should naturally evolve from a bicarbonate type in recharge areas to domination by sulfate or chloride ions in discharge areas, depending on the scale of the flow systems involved.

Based on the interpretation of the groundwater flow patterns in the last section and the hydrochemical facies map (fig. 43), an attempt can be made to link various facies types, and therefore individual chemical constituents, with areas of recharge and discharge and particular flow systems. Unfortunately, the influence of flow patterns is not strongly developed in the hydrochemical facies of the Pine Lake research basin. The concentrations of chemical constituents are probably more strongly modified from their principal concentrations by changing mineralogy, cation exchange processes, bacterial action and mixing phenomena than can be attributed to the classical Chebotarev sequence and the concept of flow systems.

Type 1 (sodium-bicarbonate) groundwaters are dominant throughout the Pine Lake area and undoubtedly represent the facies which characterizes the entire basin and upon which the other facies are superimposed. The apparent recharge areas in the hummocky moraine on the upland areas have diverse chemistries. Whether this is a result of actual areal variation in hydrochemical facies or more reflective of variable well depth is difficult to ascertain. In recharge areas, one should expect low TDS and high concentrations of bicarbonate. The reason is that groundwater acquires its principal chemical composition during infiltration into the soil and, because the environment is rich in CO_2, HCO_3^- is the most abundant species through dissolution of carbonates as follows (Davis and De Wiest 1966):

$$CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow H^+ + HCO_3^- \qquad (3)$$

$$HCO_3^- \rightarrow H^+ + CO_3^{2-} \qquad (4)$$

$$CaCO_3 + H^+ \rightarrow Ca^{2+} + HCO_3^- \qquad (5)$$

Discharge areas should be characterized by higher total dissolved solids and possibly domination of the anions by SO_4^{2-}, at least according to the Chebotarev sequence. The absence of sulfate or even sulfate-bicarbonate in the discharge area is readily apparent on the hydrochemical facies map. Clearly, the hydrochemical patterns in the Pine Lake basin do not conform to the Chebotarev sequence. Type 1 and 2 waters appear to be prominent in the recharge areas but they also characterize the mapped discharge areas around Pine Lake and Ghostpine Creek. The noticeable decrease in TDS towards these drainage ways completely disagrees with the conceptualized flow patterns. Because deeper wells are constructed along the ridges, the high TDS values in these areas are inevitably explainable for this reason alone. The distribution of type 3 (sodium-sulfate-bicarbonate) and type 4 (calcium-magnesium-sulfate-bicarbonate) groundwaters are largely restricted to mid-slope position of ridges and along the southern boundary of the basin. Some of these occurrences may be associated with local or intermediate flow systems, but they are probably controlled by local mineralogical and hydrochemical conditions. The presence of an extensive area of type 4 waters on the southern sandstone probably is a result of the highly permeable nature of the strata which reflects the chemical character of the glacial drift and shallow bedrock superimposed on the regional sodium-bicarbonate water at depth.

The limited amount of data makes it difficult to delineate unique hydrochemical facies for each hydrostratigraphic unit, especially from the maps presented earlier which contain data from wells of variable depth and springs. Furthermore, since very few wells produce groundwater from the drift deposits, the areal chemistry of this unit is not represented on the hydrochemical maps. Most domestic wells are completed in the shallow bedrock for the simple reason that drift waters are very hard and therefore are typically dominated by Ca^{2+} and Mg^{2+} as major cations and HCO_3 as the major anion, although SO_4^{2-} may be present if sufficient soluble sulfate minerals exist in the till. Ca-Mg-HCO_3 or Ca-Mg-SO_4-HCO_3 waters characterize the glacial deposits whereas Na-HCO_3 waters dominate in the bedrock (especially at depth).

The complex mineralogical assemblages which occur in the glacial drift deposits of the Pine Lake area are attributable to generation of the prominent anions and cations. As noted above, the dissolution of carbonate minerals and soil zone CO_2 is primarily responsible for the abundance of HCO_3 in shallow groundwaters. The abundance of calcareous materials in the tills and other deposits of the area are sufficient to account for the prominence of Ca-Mg-HCO_3 waters in the drift. Wallick (1977) also suggested that weathering of silicate minerals may contribute to the overall concentrations of these ions and others but recognized that carbonate equilibria is the most important control on the solubilities of Ca^{2+}, Mg^{2+}, CO_3^{2-} and frequently Fe^{2+}.

Gypsum and other sulfates also occur in drift materials and their dissolution almost always is responsible for any significant concentrations of SO_4^{2-} in drift waters. The dissolution reaction for gypsum is represented by:

$$CaSO_4 \cdot 2H_2O \rightarrow Ca^{2+} + SO_4^{2-} + 2H_2O \qquad (6)$$

In many parts of the research basin, the presence of extensive outwash deposits in the drift have precluded the concentration of SO_4^{2-}. A possible reason for this is that the strong flushing effect of local flow systems could have removed much of the soluble sulfates from the flow regime. The abundance of sulfates in shallow groundwater along the southern boundary of the research basin may be a function of the effects of higher evaporation losses in this area. As the leaching depth is shallow, small amounts of gypsiferous or pyritic material in the drift or bedrock may be a significant source of SO_4^{2-} and Ca^{2+}. The relative abundance of SO_4^{2-} in groundwaters along the eastern divide is problematic but may be due to the composition and thickness of tills.

Moderate concentrations of sodium in drift waters could be acquired through the processes of cation exchange on montmorillonitic clays, but the majority of Na-HCO_3 spring waters issuing from drift deposits around Pine Lake, Ghostpine Creek and their tributaries are probably the result of the strong influence of chemical processes dominant in the bedrock strata. These springs, therefore, are acting as inliers of bedrock hydrochemical facies rather than reflecting hydrochemical patterns in the drift.

The chemistry of groundwater encountered in the bedrock (Paskapoo Formation) of the Pine Lake area is highly dependent on the hydrogeochemistry of the glacial drift. Exceptions to this interpretation occur in the deep groundwater systems and some of the discharge areas. All have evolved, however, from shallow calcium-magnesium-bicarbonate waters in the glacial drift to a predominantly sodium-bicarbonate facies in the bedrock. Dissolution of carbonates, sulfates and other minerals still influence the concentrations of the dominant anions and cations in bedrock groundwaters, but more important now are the roles of other geochemical processes which greatly modify the primary chemical composition acquired in shallower zones. Freeze and Cherry (1979) identified four major processes: cation exchange, CO_2 generation at depths far below the water table, sulfate reduction, and oxidation of sulfide minerals.

The most likely explanation for the dominance of sodium-bicarbonate waters in the bedrock of the Pine Lake research basin is the process of cation exchange coupled with carbonate dissolution. The abundance of bentonite (for example, montmorillonite) in the rocks of the Paskapoo Formation provides ample opportunity for the replacement of Na^+ exchange sites by Ca^{2+} which is adsorbed on the clays. This process also enhances further calcite dissolution which, if maintained at low concentrations, keeps equilibrium HCO_3^- concentrations high (Freeze and Cherry, 1979). High bicarbonate concentrations can also result from sulfate reduction by oxidation of organic matter thereby generating CO_2 at depth as follows:

$$2CH_2O + SO_4^{2-} \rightarrow HCO_3^- + HS^- + CO_2 + H_2O \qquad (7)$$

This process requires an anaerobic bacteria (Hem, 1970) and is often identifiable in wells by the odor of H_2S gas. Occurrences of this phenomenon in the research basin are known and therefore biochemical sulfate reduction is a likely process for explaining the absence or low concentrations of SO_4^{2-} in many parts of the basin.

Two minor geochemical processes which are associated with carbonaceous strata in the subsurface may occur in the Pine Lake area. First, increased concentrations of HCO_3 may also be expected in coal-bearing strata due to greater amounts of CO_2. A final geochemical process which should be mentioned is the possibility of the oxidation of sulfide minerals. The presence of pyrite in coals and carbonaceous shales in the Pine Lake area is documented by a number of detailed coal exploration geologic logs (fig. 5). According to Freeze and Cherry (1979), hydrogen ions are released as a result of the reaction:

$$FeS_2 + (15/4)\,O_2 + (7/2)\,H_2O$$

$$\rightarrow Fe(OH)_3 + 4H^+ + 2SO_4^{2-} \qquad (8)$$

This oxidation must occur in the unsaturated zone and from the high production of H^+ a high HCO_3^- content can be maintained in high pH groundwaters. Note should be made that significant amounts of SO_4^{2-} is also generated and that this process can be active in drift materials derived from pyritic strata.

WATER QUALITY CONSIDERATIONS

The quality of water in the Pine Lake area can be interpreted from the maps showing the hydrochemistry (figs. 43 and 44) of the basin. All groundwaters sampled in the research basin appear to be suitable for human and livestock consumption, although some of the constituents exceed recommended drinking water standards set by the U.S. Environmental Protection Agency (1975). Quality of bedrock waters is generally superior to that of shallow drift wells because of its softer nature. The high sodium content and TDS of most of the groundwater in the basin limit its use in irrigation.

GROUNDWATER RESOURCES

Hydrogeologic investigations are incomplete without an evaluation of the groundwater resources. In groundwater exploration and development, this involves identifying and mapping major aquifers, determining quantitative hydrologic properties through aquifer testing, and predicting sustainable well yields based on the hydraulic data. For the design of a particular groundwater development, this analysis would also include an assessment of the possible impact on the existing groundwater regime. More important, however, in the context of the objective of establishing the Pine Lake research basin, is an evaluation of the subsurface components of the hydrologic cycle with emphasis on parameters such as recharge, discharge, and natural basin yield.

GROUNDWATER PROBABILITY

Figure 45 is a groundwater probability map of the research basin. "Groundwater probability" may be misleading in that figure 45 does not actually represent expected aquifer yields, but rather the anticipated range of yields for wells completed in the shallow bedrock, according to standard well-construction practices in the area.

Tóth (1966b) introduced the concept of the 20-year well yield (Q_{20}) through adaptation of the modified nonequilibrium formula (Cooper and Jacob, 1946) to arrive at the following equation:

$$Q_{20} = \frac{T\,H}{c} \qquad (9)$$

where T = transmissivity, H = total available drawdown between static water level and the top of the aquifer zone, Q_{20} = maximum flow rate that can be sustained over 20 years without drawdown below the top of the main aquifer penetrated by the well, and c = conversion factor to account for 8 cycles of time and consistency of units. The predictive accuracy of this calculation depends greatly on how representative the transmissivity value is of regional conditions. Nevertheless, this concept has been widely employed in Alberta and for purposes of consistency equation (9) has been used to produce the numerical values given in figure 45. The type of transmissivity data from which the yield points were calculated is also indicated on the map, and values of 20-year yield, transmissivity, and available drawdown are tabulated in appendix B. The complex stratigraphy and shortage of good aquifer tests prevents a detailed analysis of aquifer yield in the Pine Lake basin, and therefore only three yield ranges have been mapped: 0.1 to 0.4 L/s (1 to 5 igpm); 0.4 to 1.9 L/s (5 to 25 igpm); and greater than 1.9 L/s (25 igpm). Higher yields are widespread but differentiating them is not warranted until further pump test data are available.

The well-yield pattern in figure 45 reflects both transmissivity and water level parameters. In most parts of the basin, shallow bedrock wells can be expected to have sustained safe yields in the 0.4 to 1.9 L/s (5 to 25 igpm) range. Areas of well yield less than 0.4 L/s (5 igpm) are widespread on the western and southern ridges where poor well construction, deep static water levels, and low transmissivities are probably responsible for the existing poor yields. Wells capable of sustaining yields of 1.9 L/s (25 igpm) are found along most of are found along most of the eastern divide, near the north end of Pine Lake, and along a narrow bank just east of the western ridge. Except for a few of the wells completed in fractured shale, most produce from major sandstone aquifers. Based on the available data, sustainable 20-year well yields may exceed 7.50 L/s (100 igpm) for parts of the shallow sandstone aquifers. Where they are sufficiently thick and the hydraulic conductivity enhanced by fracturing, Q_{20} values could be even greater as suggested by some of the anomalously high values.

GROUNDWATER EXPLORATION

It was recognized early in the hydrogeologic evaluation that there were many parts of the research basin where geologic and quantitive hydrologic data were lacking, especially at depths exceeding those of domestic wells. A small exploration program was undertaken during the summer of 1979 to substantiate the hydrogeology as inferred from geophysical data. This program consisted of drilling testholes at four different locations in the Pine Lake research basin. Lithologic samples were taken at regular intervals and all four holes were electric logged. After well completion, aquifer tests of several hours duration were conducted at each site and water samples obtained for chemical analysis. These four wells have been capped but will possibly be integrated into a more extensive piezometer network in the near future.

Testhole PL79 - 1: (14-23-35-24-W4)

The location of this site was chosen for its representation of the hydrogeologic environment in the southeastern part of the research basin. Drilling to a depth of 116 m (382 ft) by cable-tool rig confirmed the presence of a massive sandstone unit which previously was inferred from geophysical data (fig. 22). The geologic results and well construction of this testhole are graphically shown in figure 46. Cable-tool drilling delineated three major zones of high hydraulic conductivity: 42.7 to 45.8 m (140 to 150 ft); 73.8 to 77.4 m (242 to 254 ft); and 108.2 to 115.2 m (353 to 378 ft). Depth to static water level dropped only slightly with depth but as drilling proceeded into the deep sandstone unit (fig. 46) water levels dropped substantially (more than a metre). Three short bail tests were conducted during drilling of the testhole, after attaining depths of 60 m (200 ft), 90 m (300 ft), and 116 m (382 ft). Interpretation of recovery levels from the bail tests is given in figure 47. The results of these tests are not adequate to quantify the vertical distribution of hydraulic conductivity. Drawdown data from a 12-hour aquifer test are shown in figure 48. Evaluation of this data by the straight-line method yielded a transmissivity value of 60 m^2/day (4020 igpd/ft^2) for the total estimated thickness of saturated sandstone at the site. Water chemistry analyses of well samples showed the most significant change at a depth of 49 m (160 ft), above which TDS is around 500 mg/L and groundwater is of the $Na\text{-}SO_4\text{-}HCO_3$ type. Sampling of groundwater below the shallow aquifer indicated that the $Na\text{-}HCO_3$ facies was dominant and that the TDS were around 850 mg/L.

Testhole PL79 - 2: (8-18-36-24-W4)

This particular testhole site was chosen because of the general absence of hydrogeologic data in the area and good central location. Although a thick shallow sandstone unit was expected to be encountered, the main object of this exploration project was to pump test in much deeper zones. The testhole was rotary drilled to a total depth of 134 m (440 ft) with 6 in steel casing installed to 86 m (282 ft) and the rest of the hole left open. Exploration data from this site are given in figure 49. Except for the basal several feet of the thick shallow sandstone, no aquifer zones were encountered in the entire section, which was dominated by shale and siltstone with minor showings of coal. The results of a 6-hour pump test on this testhole are shown in figure 50. Transmissivity was calculated to be 0.4 m^2/day. A water sample taken during the pump test was analyzed as 662 mg/L for TDS and classified as an $Na\text{-}HCO_3$ type groundwater.

Testhole PL79 - 3: (4-26-36-25-W4)

The stratigraphic data determined from the PL79-3 testhole concurred exactly with the geology inferred from nearby structure testhole electric logs. Figure 51 shows the strip lithologic log, electric logs, and construction details of this exploratory hole. A rotary rig was used to bottom the hole in a thick deep sandstone unit, 113 m (371 ft) below the land surface. Great difficulty in well construction was encountered due to a loss of cir-

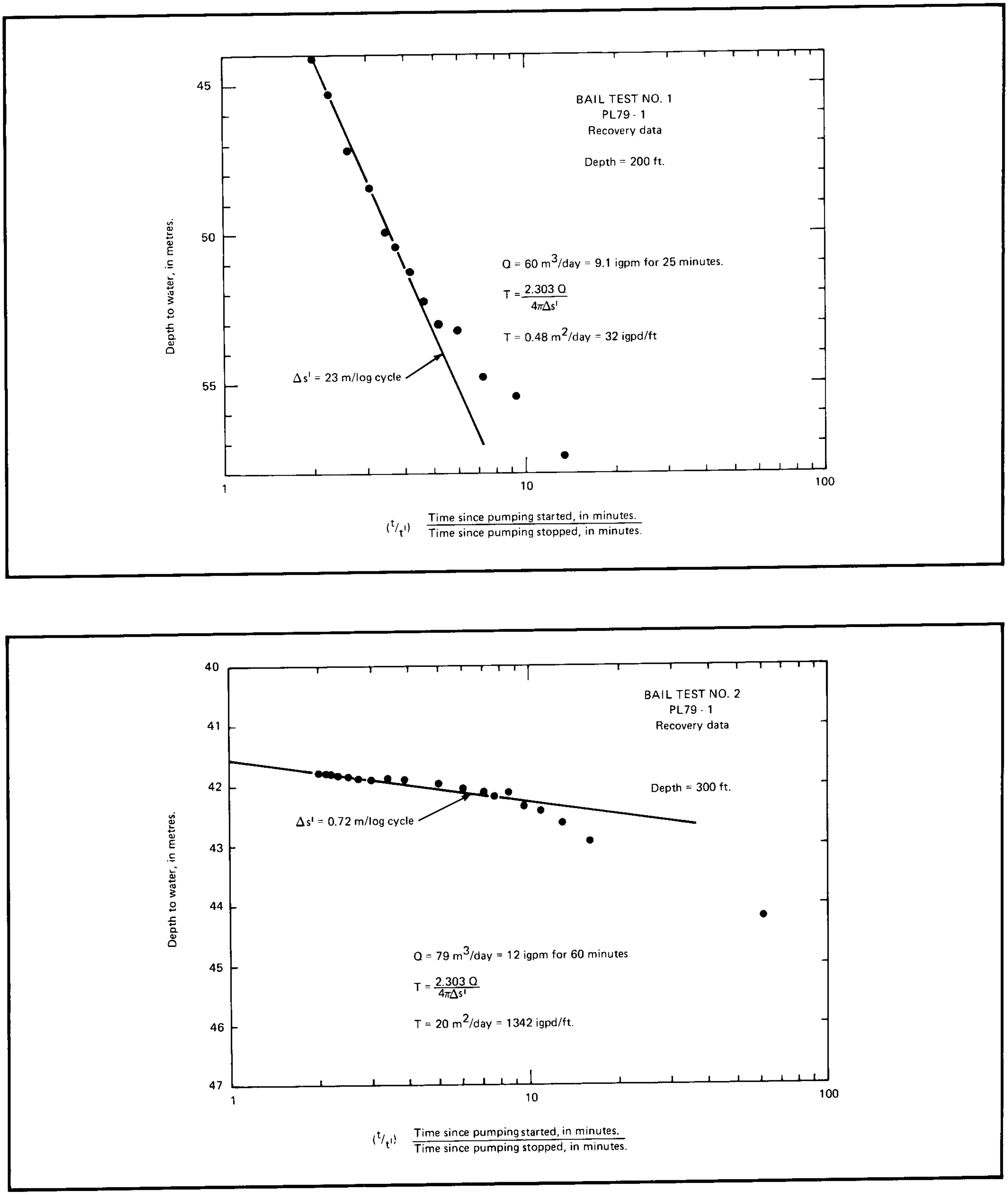

FIGURE 47. Bail-test data, PL79-1.

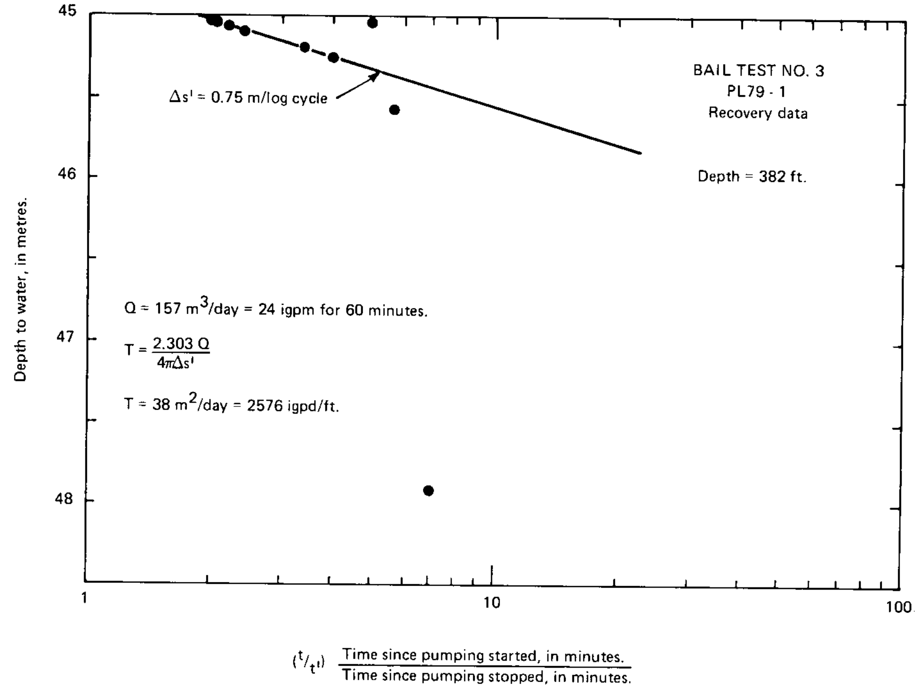

FIGURE 47. (continued)

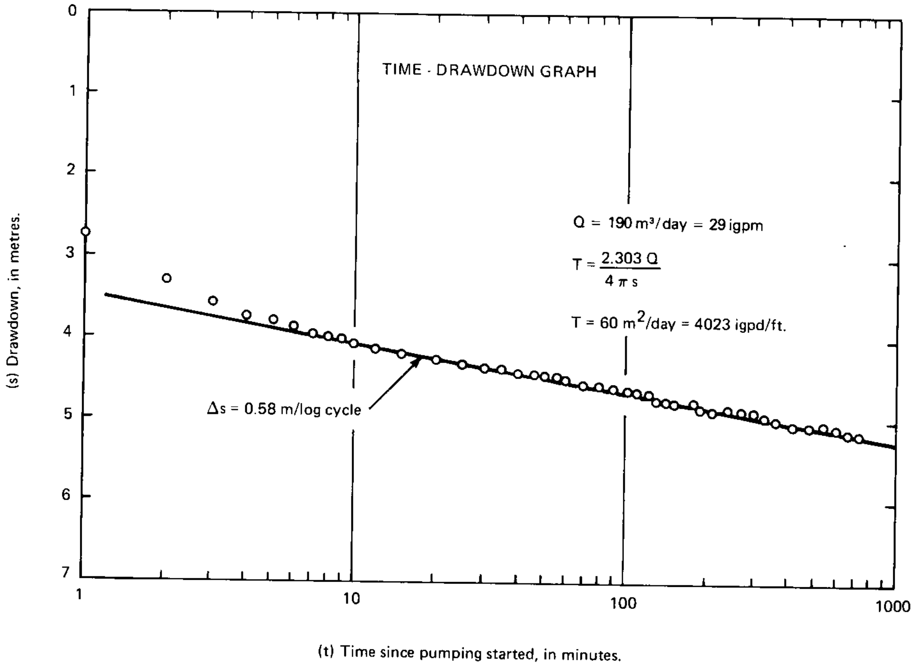

FIGURE 48. Time-drawdown graph, PL79-1.

3. Application of soil moisture budgets based on precipitation and evapotranspiration data.
4. Flow net analysis of actual field derived piezometric data.
5. The use of steady-state drainage equations.
6. Calculation of regional groundwater flow through flow net analysis of numerical models.
7. Complete water budgets of instrumented drainage basins.

The application of a few of these techniques are discussed below.

ANALYSIS OF ANNUAL WATER-TABLE FLUCTUATIONS

Tóth (1962) noted that there should be a quantitative relationship between the saturated flow of groundwater and fluctuation of the water table. Groundwater flow from recharge areas on the elevated ridges to discharge areas in the valley bottom should produce a corresponding drop and rise in the water table. At places midway between the divide and drainage way, groundwater flow is essentially lateral so the water table should remain nearly constant. In a steady-state groundwater system, the rise in water levels in discharge areas should theoretically equal the fall of levels in recharge areas for homogeneous and isotropic media. Fluctuations of water-table elevations are also, however, caused by natural and induced hydrologic phenomena, the most important of which include precipitation events, evapotranspiration, and pumping of groundwater from wells.

The most convenient time to measure the effect of groundwater flow on water-table fluctuations in western Canada is during the winter months. In the Pine Lake area, the ground is usually frozen to a depth of a few metres, depending on the amount of snow cover, and remains so throughout the months of November to March. Freezing of the ground reduces the effects of infiltration and evapotranspiration on the water table to nil and, if observation wells are not influenced by the pumping of wells, quantitative analysis of water-table hydrographs should be possible. A limiting factor of this type of analysis is the effect of the freezing process which causes moisture transfers in the unsaturated zone and thus a natural lowering of the water table. Freeze and Banner (1970) studied the relationship of soil moisture, frost, and infiltration at an instrumented experimental plot in southern Alberta. They found that the effect of freezing on lowering water tables was insignificant.

Using the notation of Tóth (1968), the natural yield of a flow system (i) for the time interval (t) is given by the equation:

$$Q_{i,t} = Sy \cdot f_{d,t} \cdot A_{i,d} = Sy \cdot f_{u,t} \cdot A_{i,u} \qquad (10)$$

where Sy = average specific yield of the rocks, $f_{d,t}$ = average drop of water levels in the area of downward flow ($A_{i,d}$), and $f_{u,t}$ = average rise of the water table in the area of upward flow ($A_{i,u}$) provided the water table fluctuations are only the result of groundwater flow from recharge to discharge areas. Equation (10) may also be expressed in terms of depth over the respective areas:

$$q_{i,t,d} = \frac{Q_{i,t}}{A_{i,u}} = Sy \cdot f_{d,t} \qquad (11)$$

and

$$q_{i,t,u} = \frac{Q_{i,t}}{A_{i,u}} = Sy \cdot f_{u,t} \qquad (12)$$

Tóth (1968) also showed that, in cases where the seasonal changes of the hydraulic gradients in the flow system are small in comparison to the average gradient, the total yield of the system ($Q_{i,T}$) over a complete annual cycle is given by:

$$Q_{i,T} = Q_{i,t} \cdot \frac{T}{t} \qquad (13)$$

This equation represents the natural basin yield if a single flow system exists in a basin; otherwise, the total natural yield would consist of a summation of the $Q_{i,T}$ for all flow systems in the basin.

Long-term water-table hydrographs are available for three shallow observation wells in the Pine Lake research basin and are here denoted as Elnora no. 2, Elnora no. 3, and Elnora no. 4. These wells are spaced almost equidistantly over the drainage divide in the southwestern corner of the basin; Figure 3 shows their exact locations. Elnora no. 2 is 5.2 m (17 ft) deep and is completed in a surficial sand deposit, presumably outwash. Elnora no. 3 is on top of the divide where it was drilled to a depth of 18.9 m (62 ft) and completed in an interbedded sequence of shale, siltstone, and sandstone. The till at this location was found to be 4.9 m (16 ft) deep. Elnora no. 4 is 13.7 m (45 ft) deep and is completed in a clayey till overlain by outwash sand. Lithologic details of this well are also given in figure 29. Alberta Research Council staff constructed these wells and automatic water-level recorders have produced hydrographs since 1962.

Presenting the complete hydrograph records for all three observation wells would be unwieldy. To illustrate the typical annual response of the water table in a recharge area, figure 55 shows the 1967 hydrograph of Elnora no. 3. One feature of all three hydrographs is the gradual rise in water levels beginning in late April and leveling off near the end of July. This feature is primarily a function of spring thaw and annual precipitation patterns and is well exhibited by the example of figure 55 (compare with figure 10). Fluctuations in the hydrograph in figure 55 for the period after May likely represent the effects of rainfall and evapotranspiration, although this pattern continues into December. The decrease of evapotranspiration throughout the early fall sustains the water-table level achieved by high precipitation in August, but eventually precipitation decreases (figs. 8 and 9) and levels drop slowly until the ground is completely frozen in early November. Because all three observation wells are in recharge areas, a drop in the water-table during the winter months (November to March) is expected due to the natural gradient of groundwater flow and the absence of recharge by precipitation. This was the case in all three observation well records and the nature of the decline shown on figure 55 is typical.

In order to quantify the effect of the groundwater

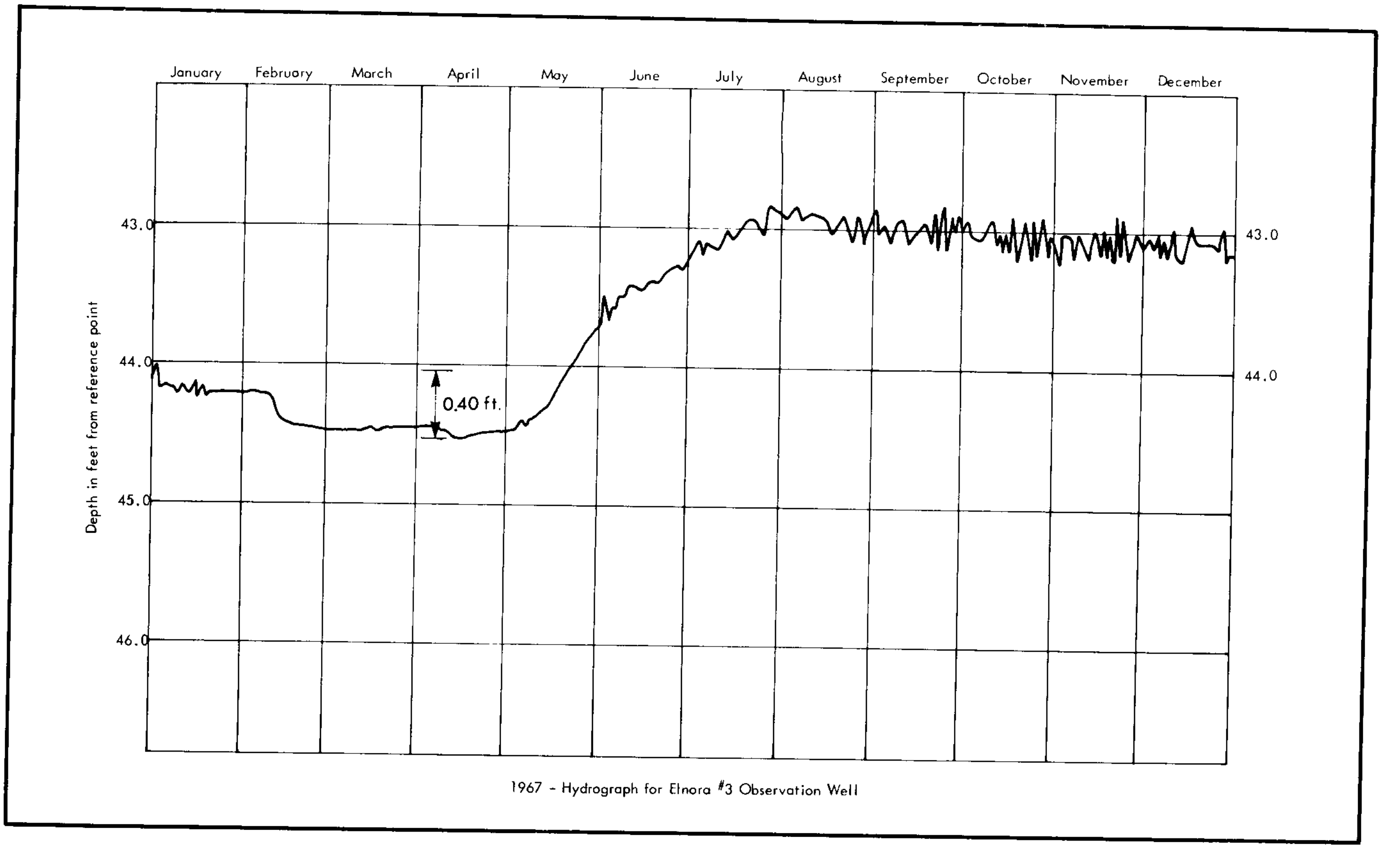

FIGURE 55. Hydrograph of an observation well in the southwestern part of the basin.

flow system on the water-table fluctuations observed in the Pine Lake area, the technique used by Tóth (1968) was applied to the hydrographs of Elnora no. 2, no. 3, and no. 4. Average changes in the water-table elevations from November to March were graphed, as shown partially in figure 55. Table 7 summarizes the results of this analysis for a 15-year record (1962-1976) and the mean water-level change calculated for a 15-year record (1962-1976) and the mean water-level change calculated for each observation well. In all of the calculations, sporadic pumping in nearby domestic wells (fig. 3) is assumed not to have affected the water table appreciably.

TABLE 7.

Summary of hydrograph analyses, groundwater observation wells. Values represent water level changes during the period November to March

(+ = rise in level, - = drop in level)

Year	Elnora #2 (feet)	Elnora #3 (feet)	Elnora #4 (feet)
1962	-0.38	+0.24	+0.02
1963	-1.56	-0.19	-0.11
1964	-0.66	0.00	-0.07
1965	-2.10	-0.32	-0.28
1966	-1.76	-0.40	-0.26
1967	-0.60	-0.44	-0.19
1968	-1.40	-0.52	0.00
1969	-1.64	-0.74	-0.15
1970	-1.48	-0.36	-0.26
1971	-1.34	-0.52	-0.26
1972	-1.58	-0.56	-0.07
1973	-	-	-0.14
1974	-2.10	-	-0.23
1975	-1.40	-	-0.20
1976	-0.75	-0.40	-0.11
Mean	-1.34	-0.405	-0.155

Based on the data given in table 7, the following calculations of average depth of groundwater exchange (Q_T) can be made with equations (11), (12) and (13), along with estimates of specific yield for the local geologic deposits:

Elnora no. 2;
$Q_T = (0.20)(1.34 \text{ ft}) \cdot (12)/(5) = 19.6$ cm (7.7 in)/year

Elnora no. 3;
$Q_T = (0.10)(0.405 \text{ ft}) \cdot (12)/(5) = 3.0$ cm (1.2 in)/year

Elnora no. 4;
$Q_T = (0.20)(0.155 \text{ ft}) \cdot (12)/(5) = 2.3$ cm (0.89 in)/year

Assuming an average annual precipitation of about 46 cm (18 in) for this part of the basin, the magnitude of groundwater exchange (recharge) represent approximately 43 percent, 7 percent, and 5 percent of annual precipitation for Elnora no. 2, no. 3, and no. 4, respectively. Tóth (1968) arrived at a value of 9 percent of annual precipitation for recharge using the same method in the Threehills drainage basin (fig. 2). Values of 5 percent and 7 percent are probably more representative of average recharge rates in the research basin than the 43 percent estimated for the surficial sand. Freeze (1969b) conducted a detailed hydrologic budget of a drainage basin in Saskatchewan and found that a large proportion of total groundwater recharge was found in a central outwash deposit. Rates of recharge in the Saskatchewan basin were calculated to dominate between 6 percent and 30 percent of annual precipitation. Since climatic conditions and surficial geology are similar to that encountered in the Pine Lake basin, the values of groundwater exchange calculated from the hydrograph analyses may indeed prove to be good preliminary estimates of areal recharge in the Pine Lake research basin.

Application of a Steady-State Drainage Equation

Meyboom (1966a) was the first to explore the possibility of using steady-state equations (originally developed for drainage of stratified soils) to calculate regional groundwater discharge in western Canada. He based his analogy on the fact that groundwater flow in a layered medium may be schematized by nearly vertical flow through an upper less permeable layer, horizontal flow through a lower permeable horizon (so-called Dupuit flow), and essentially radial flow in the vicinity of an open drainage way. Meyboom (1967a) applied the steady-state equation of Ernst (1963) to calculate groundwater discharge in the Arm River drainage basin in Saskatchewan and arrived at a numerical value consistent with that derived from the summation of baseflow and evapotranspiration estimates.

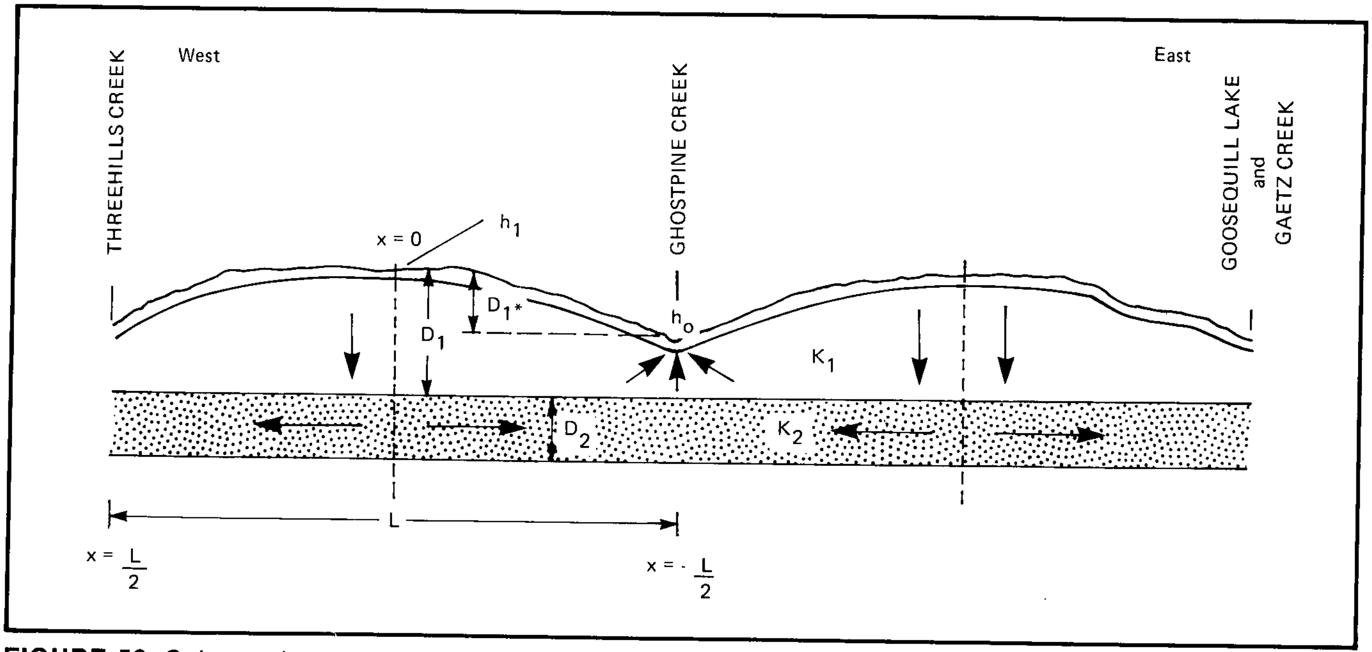

FIGURE 56. Schematic representation of groundwater flow systems across Pine Lake research basin, near the north end of the lake (h = hydraulic head, K = hydraulic conductivity, D = thickness of strata, L = distance between parallel drainage channels).

The similarity of Meyboom's (1967a, fig. 3) schematic representation of groundwater flow in the Arm River basin to that inferred for the Pine Lake research basin (fig. 39) encouraged the writer to try Meyboom's method of analysis.

A schematic representation of groundwater flow across the Pine Lake research basin is given in figure 56. This diagram, based on the conceptual model presented in figure 39, may not hold for all parts of the Pine Lake basin. Nevertheless, the hydrogeologic model of a symmetric drainage basin consisting of a permeable layer overlain by a thicker, less permeable unit will serve as a first approximation to the actual complex stratigraphy. The steady-state drainage equation for this particular hydrogeologic configuration derived by Ernst (1963) and used by Meyboom (1967a) is:

$$h_1 - h_o = Nc_1 + \frac{NL_2}{8(K_1D_1 + K_2D_2)} + NLw \qquad (14)$$

where the coefficients are defined and evaluated for the Pine Lake basin as follows (fig. 56):

L = distance between parallel drainage basins = 13 km

h_1 = total hydraulic head of the water table at the drainage divide = 945 m
h_o = water level in the drainage channel=890 m
D_1 = thickness of the low permeability layer = 90 m
D_2 = thickness of the deep permeable unit = 55 m
K_1 = hydraulic conductivity of the low permeability layer = 0.1 m/day
K_2 = hydraulic conductivity of the permeable sandstone unit = 2.0 m/day
D_1* = thickness of the low permeability layer midway between drainage channels and to a depth equal to the bottom of the channel (fig. 56) = 60 m
c_1 = D_1*/K_1 = vertical resistance = 667 days
D_1** = thickness of the low permeability layer at the drainage way = 55 m
R_o = radius of the wetted perimeter of the drainage channel = 5 m
w = $1/\pi K_1 \cdot \ln(4D_1^{**}/Ro)$ = vertical resistance = 11 days/m
N = total groundwater discharge confined to the drainage way. Similar drainage equations are also presented by Bear (1979).

Solving Equation (14) for the value of groundwater discharge results in N = 5 cm/yr (2 in/year) or approximately 11 percent of the annual precipitation. The steady-state drainage equation of Ernst (1963) requires the following assumptions: (1) the strata are of constant thickness, (2) each layer is homogeneous and isotropic, (3) $(D_1 + D_2)/L$ less than 0.25, (4) K_1D_1 less than 0.1 $K_2\ D_2$, (5) the water table is nearly horizontal, (6) drainage takes place by parallel streams only, and (7) groundwater discharge is restricted entirely to the drainage channel. Although several assumptions are met or closely approximated in the Pine Lake basin, whether or not it is realistic to assume restriction of groundwater discharge to the drainage channel in light of the field mapping (fig. 38) is questionable.

Interpretation of Streamflow Records

The method of baseflow separation as a means for estimating regional groundwater discharge has received considerable attention in western Canada (Meyboom, 1961; Farvolden, 1963b; Tóth, 1968; Freeze, 1969a). Based on two years of records, crude estimates of annual groundwater runoff over the drainage area amount to 0.4 cm (0.17 in) and 0.3 cm (0.11 in) for the years 1967 and 1969. According to these figures, groundwater discharge to the drainage ways amounts to only about 1 percent of annual precipitation.

Natural Basin Yield

Freeze and Witherspoon (1968) defined the natural basin yield as the natural quantity of groundwater flow through an undeveloped drainage basin. It is easily calculated from quantitative flow nets and provides an estimate of the amount of groundwater that can be safely withdrawn from a basin. Freeze (1971) showed, however, that a much more detailed assessment is required to obtain quantitative values of optimum or safe yield.

As a first approximation, we can make use of figure 40 to calculate natural yield in the Pine Lake research basin. This particular simulation gave rise to two major flow systems. The regional system consists of nearly vertical flow across the low permeability units to sub-horizontal flow through the sandstone aquifers. Superimposed near the regional discharge area is a very strong local flow system. Using the hydraulic conductivities specified and Darcy's law, the natural discharge through the regional system is 15 m^3/day (per metre of thickness perpendicular to the section). A similar calculation for the local flow system gives a value of 40 m^3/day/m (2800 igpd/ft). Total groundwater discharge through this part of the basin is, therefore, approximately 55 m^3/day/m (4000 igpd/ft). Obviously, the area near Pine Lake would seem to be the optimal location for any major groundwater development project.

Actual rates of recharge across the basin cannot be immediately determined from figure 40 without accurate hydraulic conductivity measurements of the glacial drift. At present, only an estimate can be made through the published values of permeability (till) given earlier. If we assume a vertical hydraulic conductivity of 5×10^{-5}m/day (10^{-3} igpd/ft^2) and use a hydraulic gradient of 0.7 (from figure 40), then an estimated recharge rate is 1.3 cm/yr (0.5 in/yr). This value would be considerably higher for the outwash deposits around Pine Lake.

WATER BALANCE CONSIDERATIONS

In its simplest form, the hydrologic budget equation or water balance is:

$$I - O = dS/dt \qquad (15)$$

which states that the inflow into a hydrologic system during a given period minus the outflow during a given period must equal the change in storage within the system. An extension of this simple water budget equation to the Pine Lake research basin would have to be considerably more detailed in order to quantify all the hydrologic components. Such an equation could be written for an annual period as:

$$P + R_i - R_o + G_i - G_o - ET - Q_p = S_s + S_g \qquad (16)$$

where P = precipitation, R_i = surface runoff into the basin, R_o = surface runoff out of the basin, G_i = groundwater flow into the basin, G_o = groundwater flow out of the basin, ET = evapotranspiration, Q_p = total groundwater pumpage for domestic and livestock purposes, S_s = change in storage of surface-water reservoirs, and S_g = change in storage of groundwater system (saturated and unsaturated zone).

If it can be assumed that the groundwater divide coincides with the surface divide (fig. 41), $R_i = 0$ and if groundwater pumpage is negligible, $Q_p = 0$. Equation (16) can be further simplified by considering a long period of time (several years) such that $G_i = G_o$ (throughflow) and $S_s = S_g = 0$, hence;

$$P - R_o - ET = 0 \qquad (17)$$

where P is now the average annual precipitation, R_O = average annual surface runoff, and ET = average annual evapotranspiration. Given the values of precipitation and streamflow runoff, average annual evapotranspiration could be estimated using equation (17), a parameter that is often difficult to measure in the field. Assuming that the average annual precipitation for the Pine Lake research basin (table 1) is approximately 46 cm and that the average annual runoff is 2 cm over the basin, mean annual evapotranspiration over the research basin can be crudely estimated by equation (17):

$$ET = P - R_O = 44 \text{ cm } (17.2 \text{ in})$$

This value can be compared with the potential evapotranspiration of 51 to 53 cm (20 to 21 in) calculated in table 1 and that of actual evapotranspiration estimated as 41 to 46 cm (16 to 18 in) by the Government and University of Alberta (1969).

Without more quantitative hydrologic data, a detailed analysis of the water budget in the Pine Lake basin would be unfounded. Freeze and Cherry (1979) concluded that applying steady-state water-budget equations is in reality inadequate for accurate evaluations of the hydrologic regime of a drainage basin. They base this statement on the fact that the approach does not take into account the areal and temporal variations in precipitation, evapotranspiration, runoff, recharge, or discharge. Nevertheless, studies have shown (Freeze 1969a, 1969b) that with a minimum amount of instrumentation and logical assumptions, a significant understanding of both the groundwater and surface water regime can be achieved through the application of simple, lumped-parameter water budget equations.

CONCLUSIONS AND RECOMMENDATIONS

As outlined at the beginning of the text, the main purpose of this evaluation was to provide a preliminary framework for instrumentation and future hydrologic studies. Before examining these research possibilities, a summary of the major findings is presented.

SUMMARY AND CONCLUSION

Geographical Aspects

(1) The Pine Lake research basin comprises a 230 km² (90 sq mi) portion of the much larger Ghostpine Creek drainage basin. Topography is rolling to hilly and maximum relief is approximately 180 m (600 ft). The present topography is essentially a subdued replica of a buried bedrock topography.

(2) Drainage is moderately developed in the basin, except in extensive areas of knob-and-kettle terrain where no integrated surface drainage exists. Pine Lake and Ghostpine Creek are the major hydrographic features in the basin. Ghostpine Creek is an intermittent stream where streamflow is highly regulated by surface runoff. Pine Lake is a permanent body of water that receives a significant amount of local groundwater discharge.

(3) The research basin is dominated by the Black Soil Group which reflects the surficial geology. These soils support a healthy phreatophytic vegetation and, therefore, transpiration loss of soil moisture is a major component of the local hydrologic cycle.

(4) Mean annual precipitation is approximately 46 cm (18 in) and potential evapotranspiration was calculated by the Thornthwaite method to be about 51 cm (20 in) annually. A crude water-budget calculation yielded an actual evapotranspiration of 44 cm (17 in) as an annual mean over the basin.

(5) Physiography has a substantial influence on groundwater in the Pine Lake area. Most important is its control on the rates and distribution of recharge and the pattern of groundwater flow. Unfortunately, field data is currently not available to quantify this observation.

Geology

(1) The entire basin is underlain by bedrock strata of the Paskapoo Formation. It is characterized by a complex succession of sandstone, siltstone, shale, and minor coals which exhibit a very gentle structural dip to the west. The Paskapoo Formation ranges from about 110 m (350 ft) thick in the south to over 360 m (1200 ft) in the northeastern part of the research basin.

(2) The Lower Ardley 'B' coal zone is the most persistent marker bed in the Paskapoo Formation. The sequence of strata above the coal zone contains two regionally extensive units dominated by

sandstone beds: a deep basal unit that averages about 60 m (200 ft) thick and a near-surface unit that is usually less than a 30 m (100 ft) thick. The shallow sandstone unit is the major aquifer in the Pine Lake basin.

(3) The glacial drift is generally less than 15 m (50 ft) thick, but can exceed 43 m (140 ft) in areas of hummocky moraine and along a buried bedrock drainage way currently occupied by Pine Lake and Ghostpine Creek. Till is the most abundant drift material. Deposits of sands and gravel are found in outwash deposits near Pine Lake, along Ghostpine Creek, and in a few esker ridges.

Hydrologic Results

(1) Based on two years of streamflow data, annual surface runoff may be in the magnitude of 2 cm (0.08 in) over the drainage basin. Estimating the baseflow component from such scanty runoff data is highly questionable, although an "average" value of 0.36 cm (0.14 in) was calculated using minimum monthly discharges.

(2) Pine Lake is a major groundwater discharge feature. It is difficult to perform a meaningful water budget of this system, without quantitative data of evaporation rates, surface water inflows and outflows. Analysis of Lake level hydrographs (4 years) yielded a mean annual net evaporation equal to 48 cm (19 in).

(3) The water table is a subdued replica of the topography. Regional groundwater flow is from broad recharge areas on the surrounding uplands and hummocky terrain towards wide discharge areas centered along the drainage ways. This is supported by the fact that hydraulic heads are observed to decrease with depth on the drainage ridges and increase with depth along the valley bottom. In addition, flowing wells and numerous springs are concentrated in the vicinity of major topographic lows.

(4) Pump-test data and geological considerations indicate the following ranges of hydraulic conductivity: sandstone, 0.5 to 25 m/day (10 to 500 igpd/ft^2); siltstone, 0.25 to 0.50 m/day (5 to 10 igpd/ft^2); shales, 0.05 to 0.25 m/day (1 to 5 igpd/ft^2); sand and gravel 5 to 100 m/day (100 to 2000 igpd/ft^2); and till, 10^{-5} to 10^{-2} m/day (10^{-3} to 1 igpd/ft^2). Anisotropy ratios are estimated to be about 50 to 100:1 for the bedrock, 10:1 for the till, and 1:1 for surficial sands and gravels. Field-determined storage coefficients are rare, but most bedrock aquifer tests can be expected to obtain storativities in the 10^{-4} to 10^{-2} range, depending on the degree of local confinement.

(5) Four major hydrostratigraphic units are delineated: unit 1 is assigned to the glacial drift; unit 2 includes those strata presently penetrated by domestic wells, down to the top of the thick basal sandstone; unit 3 is assigned to the strata of the thick basal sandstone, down to the Lower Ardley 'B' coal zone; and unit 4 to the rocks below the coal zone. Such a division is partly conjectural, but it provides a base upon which future studies can build.

(6) Groundwater flow in the research basin is most appropriately treated as a regionally unconfined system in a heterogeneous and anisotropic rock media. The absence of regional confining units and the hydraulically connected nature of the subsurface strata support this interpretation. As a first approximation, the groundwater regime can also be considered to be in steady state. This is supported by the fact that the configuration of the water table has not changed appreciably over the years, fluctuations of water-table levels are small compared to the saturated thickness of the system, and pumping of groundwater in the basin is insignificant. A numerical model, based on these assumptions, gave a simulated flow pattern which qualitatively agrees with the conceptual-field model of flow in the Pine Lake basin.

Hydrogeochemistry

(1) The complex mineralogical assemblages in the glacial drift and operation of geochemical processes during infiltration are largely responsible for determining the existing hydrochemical facies pattern. Sodium-bicarbonate is by far the most prominent hydrochemical facies in the bedrock, but superimposed upon it are facies of Ca-Mg-HCO_3, Na-SO_4-HCO_3, and Ca-Mg-SO_4-HCO_3. Total dissolved solids are usually less than 1000 mg/L in the groundwater, at least within 90 m (300 ft) of the surface.

(2) Drift groundwaters are usually hard and characterized by the Ca-Mg-HCO_3 facies or Ca-Mg-SO_4-HCO_3 facies where soluble sulfate minerals are present. Geochemical processes such as cation exchange and sulfate reduction are responsible for the transition of these shallow "recharge" facies to the dominant Na-HCO_3 water at depth.

(3) In general, correlation of hydrochemical facies with groundwater flow patterns is currently untenable and should receive considerably more research before major conclusions are drawn.

Groundwater Resources

(1) Nearly all wells in the Pine Lake basin are completed in bedrock aquifers, mainly because of ease in well construction, better water quality, and higher probability of penetrating a dependable supply of water. In most parts of the basin, shallow bedrock wells should be able to obtain sustained 20-year safe yields in the 0.4 to 1.9 L/s (6 to 25 igpm) range. Wells completed in the thick shallow sandstone unit may be capable of exceeding 7.5 L/s (100 igpm) in parts of the research basin.

(2) A major conclusion to be drawn from the exploration program is that significant groundwater resources exist in the deep, thick sandstone units, but hydraulic conductivity is highly regulated by lithological facies. Furthermore, the program demonstrated that deep groundwater flow systems exist in the research basin, as predicted by theoretical considerations.

(3) Through the analysis of water-table fluctuations in three observation wells in a recharge area, the average depths of recharge amounted to 20 cm (7.7 in), 3 cm (1.2 in), and 2 cm (0.9 in), annually. Application of a steady-state drainage equation to a schematic representation of the Pine Lake basin resulted in an estimate of annual discharge of 5 cm (2 in) over the basin. Quantitative evaluation of the distribution of groundwater recharge will require a more sophisticated approach than those above if meaningful groundwater budgets are to be performed. A preliminary numerical model indicates that natural basin yield is about 55 m^3/day/m (4000 igpd/ft). Nearly three times as much flow occurs in the local flow system around Pine Lake as passes through the regional groundwater flow system.

RECOMMENDATIONS

Instrumentation

In terms of evaluating the quantitative aspects of the groundwater regime, some form of piezometer grid must be established in the Pine Lake basin. Based on the preliminary assessment of the hydrogeology and groundwater flow pattern, the most functional design would consist of several piezometer nests arranged in a line and kept approximately parallel to the maximum topographic gradient. Ideally, it would be very useful to have three of these line networks, one across each of the northern, central, and southern parts of the research basin. Because of the near symmetry of the basin, individual lines would only need to extend from one drainage divide to the valley bottom, but at least one should extend across the complete basin to investigate the symmetry hypothesis.

Although the number of nests along each piezometer line could be varied with the local conditions, a minimum of three would be required: one near the ridge, one midway on the basin's flank, and one at the drainage way. This initial instrumentation phase could later be expanded by installing piezometer nests between existing ones and so on.

Individual piezometer nests would have to be designed for the local site conditions. On the ridges this could entail locating the deepest piezometer at a depth of 150 m (500 ft) or more. Towards the drainage bottoms, maximum piezometer depth would not need to exceed 120 m (400 ft) in order to penetrate the main hydrostratigraphic units. Each nest should consist of at least three piezometer openings completed at some arbitrary depth interval, either in separate small-diameter boreholes side by side or possibly in the same hole.

Commercial piezometer units offer a number of sophisticated designs. These units use a variety of pressure transducers, packer assemblies, and advanced electronics to take measurements of head or hydraulic conductivity and to obtain samples for chemical analysis at several piezometer openings. In addition to a sufficient number of piezometers at a site, a water-table well should also be installed and equipped with a recorder. Good estimates of hydraulic conductivity can be obtained from the piezometers by applying the Hvorslev (1951) method on recovery data.

Instrumentation of the unsaturated zone should also be considered. Experimental plots could be established at both a recharge and discharge area and the relationship between infiltration, evapotranspiration, soil moisture, and groundwater recharge or discharge investigated. This type of site could include a precipitation gauge, neutron probe access tubes, water-table observation well, tensiometers, and perhaps a shallow piezometer nest.

A complete instrumentation plan for the subsurface should not ignore surface water completely. Only one meteorological station currently exists in the basin, and that is in the northern reaches. Temporary precipitation gauges should be established, preferably to the west of Pine Lake and in the southern part of the basin. Runoff is one of the easiest components of the hydrologic cycle to measure in the field and such data would be desirable for the Pine Lake research basin. Establishing a permanent streamflow gauging station at the southern outlet of the research basin is a prerequisite. Temporary stations would have to be installed at the major inlets and outlets of Pine Lake if a serious analysis of its water budget is attempted in the future. The actual interaction between Pine Lake and the groundwater regime would best be defined through piezometric analyses and installation of seepage meters.

Future Study

It is apparent from this investigation that significant amounts of information can be derived from careful interpretation of basic data. The exploration program was successful at confirming the accuracy of this data. Future drilling programs should concentrate on obtaining hydraulic conductivities of the deep sandstone aquifers and properties of the unsaturated zone. Now that the hydrogeology has been studied, research emphasis should be shifted from data collection to experimentation with new field techniques or technology.

Perhaps the most important recommendation that can be made is more application of numerical modelling techniques. As the general aspects of the hydrogeologic environment and groundwater regime have been determined, numerical modelling of the basin could provide additional insight. Detailed flow net studies could be used to identify the spatial distribution of recharge and discharge and quantitatively investigate their orders of magnitude for various boundary conditions. Numerical modelling could also be integrated with future field programs to help the researcher decide on optimal locations of piezometers or other instrumentation. The role of modelling in understanding the interaction between Pine Lake and the groundwater flow systems could be invaluable. Time-series analysis of both groundwater and lake-level hydrographs may also provide interesting answers to the interaction problem. The idea here is not necessarily to provide numbers but rather insight into the hydrology of the basin.

Hydrogeochemistry is poorly understood in the basin and deserves future research considerations in two major areas. First, geochemical evaluation of groundwaters could be investigated using the techniques put forth by Schwartz and Domenico (1973) or Plummer and Back (1980). Sophisticated computer programs are currently available that make studies of this type tenable. Second, an effort should be made to obtain dispersivity data and establish monitoring sites. Not only would this be of local benefit for environmental reasons, but as there are few field-research sites in western Canada, the Pine Lake basin would make an ideal candidate.

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APPENDIX A: Shallow Well and Spring Data

Notes to Appendix A

1. Column 3: Elevation of land surface in the vicinity of the well as determined by extrapolation from topographic map with 25 ft contour interval.
2. Column 9: Type of well refers to the geology of the material in which the well is completed.
3. Column 11: Available drawdown (H) is defined as the difference between static water level and the top of an aquifer.
4. Column 12: T = transmissivity, K = hydraulic conductivity as determined from bail test.
5. Column 13: Q_{20} = maximum discharge rate which can be sustained over a 20-year period without drawdown below the top of an aquifer (calculated by $Q_{20} = (T)(H)/2110$).

Index Number	Location	Elevation (map) In feet a.m.s.l.	Depth of Well (ft.)	Construction, Depth Interval Open to Aquifers (feet)	Use	Depth to Water Elev. (feet)
1	5-1-35-24W4	2825	70		Shothole	Flowing 2825 +
2	9-2-35-24W4	2825	75		Domestic	Flowing 2825 +
3	3-4-35-24W4	2980	140	100 - 140	Domestic stock	90.2 2890
4	8-4-35-24W4	2970	108		Domestic stock	35 2935
5	10-7-35-24W4	3110	190		Domestic	
6	14-7-35-24W4	3085	122	70 - 122	Domestic stock	69 3016
7	14-9-35-24W4	3050	150		Domestic	131 2919
8	5-9-35-24W4	3030	230	221 - 230	Domestic	130 2900
9	16-9-35-24W4	3045	252		Domestic stock	180 2865
10	16-9-35-24W4	3045	262	240 - 262	Domestic stock	170 2875
11	10-9-35-24W4	3060	190	140 - 190	Stock	123 2937
12	7-10-35-24W4	2910	300			30 2880
13	15-12-35-24W4	3055	230		Domestic	60 2995
14	1-13-35-24W4	3035	215		Domestic	
15	9-13-35-24W4	3035	210			170 2865
16	16-14-35-24W4	3075	266	200 - 266	Domestic	221 2854
17	1-15-35-24W4	2875	85			15 2860
18	8-15-35-24W4	2870	118		Domestic	10 2860

Depth to Bedrock Elev. (feet)	Type of Well	Lithology of Aquifer	Available Drawdown (feet)	T (igpd/ft.) and K (igpd/ft.^{2})	Q_{20} (igpm)	Other Remarks
	Bedrock?					Chem. analysis available
27 2953	Bedrock	Sandstone	40	90 (K = 2)	2	No recovery
						Chem. analysis available
						Chem. analysis available
25 3060	Bedrock	Fractured Sandstone	50	400 (K = 76)	9	Recovery data
	Bedrock	Sandstone				
20 3010	Bedrock	Sandstone	90			Pumped at 5 gpm
	Bedrock					Chem. analysis available
15 3030	Bedrock	Sandstones	90	550 (K = 6)	24	Recovery date
27 3033	Bedrock	Fractured Shale Siltstones	63	940 (K = 14)	27	
	Bedrock					Chem. analysis available
	Bedrock					Chem. analysis available
						Chem. analysis available
	Bedrock					Chem. analysis available
	Bedrock					
	Bedrock					Chem. analysis available

Index Number	Location	Elevation (map) In feet a.m.s.l.	Depth of Well (ft.)	Construction, Depth Interval Open to Aquifers (feet)	Use	Depth to Water Elev. (feet)
19	8-17-35-24W4	3050	90	70 - 90	Stock	30 3020
20	1-18-35-24W4	3045	65			40 3005
21	15-19-35-24W4	2950	15		Stock	3 2947
22	2-20-35-24W4	3000	80	48 - 80	Stock	41.5 2958
23	14-20-35-24W4	2920	96	71 - 96	Domestic	35 2885
24	NW-20-35-24W4	2890	30			Flowing 2890 +
25	8-21-35-24W4	2875	58		Domestic	22 2853
R.C.A. #77-4	13-21-35-24W4	2870	150		Testhole	Flows 2870 +
26	12-22-35-24W4	2910	132	112 - 132	Stock	40 2870
27	4-23-35-24W4	2900	60			9 2891
28	15-24-35-24W4	3040	230	190 - 230	Domestic	160 2880
29	1-26-35-24W4	3060	286		Domestic	50 3010
30	5-26-35-24W4	3085	260		Domestic stock	120 2965
31	5-26-35-24W4	3085	250		Domestic	191 2894
32	13-26-35-24W4	3115	240	186 - 240	Domestic stock	143 2972
33	13-26-35-24W4	3115	158			
33.5	11-28-35-24W4	2915	160	145	Domestic stock	20 2895
34	2-29-35-24W4	2950	81	70 - 81	Stock	60 2890
35	8-29-35-24W4	2885	140	120 - 140	Domestic	23

Depth to Bedrock Elev. (feet)	Type of Well	Lithology of Aquifer	Available Drawdown (feet)	T (igpd/ft.) and K (igpd/ft.^{2})	Q_{20} (igpm)	Other Remarks
35 3015	Bedrock	Sandstone (Coal?)	55	300 (K = 18)	8	Chem. analysis available
37 2963	Bedrock	Sandstone	30	28,610 (?)	407	Chem. analysis available
45 2875	Bedrock	Sandstone	50+	1635 (K = 65)	39	
	Bedrock ?					Chem. analysis available
1327 2738		Sand, Gravel Sandstone				
28 2882	Bedrock	Sandstone, Siltstone (fractured)	60	7330 (K = 163)	208	Chem. analysis available
43 2997	Bedrock	Sandstone	60	150 (K = 2.8)	4	
19 3041	Bedrock	Shale no aquifers				1 gpm well abandoned
19 3066	Bedrock	Shale Siltstones	120	20 (K = 2)	1	No log available
25 3060	Bedrock	Sandstone	50			
55 3060	Bedrock	Sandstone	85	3960 (K = 43)	160	
	Bedrock					Chem. analysis available
45 2870	Bedrock	Fractured shale, coal	130	50 (K = 4)	3	Recovery data
14 2936	Bedrock	Sandstone	15+	1310 (K = 66)	9	Chem. analysis available
117 2768	Bedrock	Sandstone	110	13,080 (K = 174)	680	

Index Number	Location	Elevation (map) In feet a.m.s.l.	Depth of Well (ft.)	Construction, Depth Interval Open to Aquifers (feet)	Use	Depth to Water Elev. (feet)
						2862
36	2-30-35-24W4	2980	60	40 - 60	Domestic	39 2941
37	4-30-35-24W4	3010	110		Domestic	55 2955
38	4-31-35-24W4	3020	50		Domestic	30 2990
39	NE-31-35-24W4	2975	146	106 - 146	Stock	65 2910
40	NW-31-35-24W4	3030	96			35 2995
41	12-32-35-24W4	2930	80			20 2910
42	9-33-35-24W4	3025	60		Shothole	Flowing 3025+
43	1-34-35-24W4	3095	160	130 - 160	Domestic stock	121 2974
44	1-34-35-24W4	3095	135		Domestic stock	100 2995
45	4-34-35-24W4	3010	70	52 - 70	Domestic stock	42 2968
46	12-35-35-24W4	3110	215		Domestic	
47	1-36-35-24W4	2957			Shothole	Flowing 2957+
48	SE-36-35-24W4	3025	3		Spring	3 3022
49	12-1-35-25W4	3095	96		Domestic	50 3045
50	12-2-35-25W4	3035			Shothole	Flowing 3035+
51	9-3-35-25W4	3030			Shothole	Flowing 3030+
52	4-9-35-25W4	3025	115	100 - 115	Domestic	30 2995
53	1-10-35-25W4	3030	98	84 - 98	Domestic stock	35 2995
54	14-12-35-25W4	3130	150		Domestic	20 3110

Depth to Bedrock Elev. (feet)	Type of Well	Lithology of Aquifer	Available Drawdown (feet)	T (igpd/ft.) and K (igpd/ft.^{2})	Q_{20} (igpm)	Other Remarks
36 2944	Bedrock	Sandstone shale	15+	29,930	190	
	Bedrock	?				Chem. analysis available
	Drift?					Chem. analysis available
36 2939	Bedrock	Sandstone	75	3120 1950	110	Recovery data
						Chem. analysis available
						Chem. analysis available
51 3044	Bedrock	Sandstone	35+	23,880 (K = 220)	396	
35 2975	Bedrock	Sandstone	25+	53,990	640	Recovery data
	Bedrock					Chem. analysis available
	Drift					Chem. analysis available
85 2940	Bedrock	Shale, Sandstone	70+			Chem. analysis available
82? 2948	Bedrock	Sandstone	50			
	Bedrock					Chem. analysis available

Index Number	Location	Elevation (map) In feet a.m.s.l.	Depth of Well (ft.)	Construction, Depth Interval Open to Aquifers (feet)	Use	Depth to Water Elev. (feet)
55	2-13-35-25W4	3140	65		Domestic stock	45 3095
56	13-13-35-25W4	3120	220	180 - 220	Domestic stock	115 3005
57	13-13-35-25W4	3120	205	170 - 205	Domestic stock	120 3000
58	13-13-35-25W4	3120	290		Domestic stock	140 2980
59	4-15-35-25W4	3100	102	60 - 102	Domestic stock	42 3058
60	4-15-35-25W4	3100	60		Stock	27 3073
61	1-17-35-25W4	3075	125	87 - 125	Domestic stock	72 3003
62	15-20-35-25W4	3150	158	98 - 158	Domestic stock	104 3046
63	15-21-35-25W4	3150	90	65 - 90	Domestic stock	23 3127
64	16-21-35-25W4	3120	78		Stock	15 3105
65	16-22-35-25W4	3150	205			100 3050
66	8-23-35-25W4	3075	130	110 - 130	Domestic stock	85 2990
67	SE-25-35-25W4	3025	125		Domestic	120 2905
68	4-25-35-25W4	3065	132		Domestic	120 2945
69	2-27-35-25W4	3190	183	118 - 183	Domestic stock	87 3103
70	2-27-35-25W4	3190	220	180 - 220	Domestic	159 3031
71	9-27-35-25W4	3125	164	144 - 164	Domestic stock	123 3002
72	2-28-35-25W4	3180	115	90 - 115	Domestic stock	52 3128

Depth to Bedrock Elev. (feet)	Type of Well	Lithology of Aquifer	Available Drawdown (feet)	T (igpd/ft.) and K (igpd/ft.^{2})	Q_{20} (igpm)	Other Remarks
32 3088	Bedrock	Sandstones	85	240 (K = 3)	10	
24 3096	Bedrock	Sandstones	80	50	2	Recovery data
	Bedrock					Chem. analysis available
38 3062	Bedrock	Sandstone, coals	50+			Chem. analysis available
	Bedrock ?					Chem. analysis available
84 2991	Bedrock	Fractured shale	45	370 (K = 10.6)	8	Chem. analysis available Recovery data
80 3070	Bedrock	Sandstone	50	180 (K = 4.5)	4	
31 3119	Bedrock	Sandstone coal	50	3060 (K = 50)	73	
25 3050	Bedrock	Sandstone	40	4670 (K = 40)	88	Recovery data Chem. analysis available
	Bedrock					Chem. analysis available
						Chem. analysis available
95 3095	Bedrock	Sandstone coal	90	245 (K = 3)	10	Chem. analysis available
4 3186	Bedrock	Sandstone coals	55+		>20	
24 3101	Bedrock	Sandstone	35+	4670 (K = 29)	>78	Recovery data
28 3152	Bedrock	Fractured siltstone, shale	45	102 (K = 1.7)	> 2	

Index Number	Location	Elevation (map) In feet a.m.s.l.	Depth of Well (ft.)	Construction, Depth Interval Open to Aquifers (feet)	Use	Depth to Water Elev. (feet)
73	3-29-35-25W4	3150	17			4 3146
74	3-30-35-25W4	3050	8002		Oil well or gas	
75	SW-32-35-25W4	3190	Spring		Stock	3190 +
76	6-34-35-25W4	3089	3275		Oil or Gas Well	
77	12-34-35-25W4	3175	200		Domestic	100 3075
78	12-35-35-25W4	3075	220	160 - 220	Domestic	94 2981
79	NE-36-35-25W4	3035	118		Domestic	20 3015
81	4-2-36-24W4	3150	100	80 - 100	Domestic stock	79 3071
82	13-2-36-24W4	3100	300	240 - 300	Domestic	204 2896
83	13-2-36-24W4	3100	190	50 - 190	Domestic stock	92 3008
84	SE-3-36-24W4	3100	257			157 2943
85	SE-4-36-24W4	3035	70	67 - 70	Stock	50 2985
86	13-4-36-24W4	3010	50			40 2970
87	16-4-36-24W4	3030	?		Shothole	0 3030 +
88	13-5-36-24W4	2925	65	60 - 65	Domestic	0 2925 +
89	13-5-36-24W4	2920	60		Shothole	0 2920 +
R.C.A. #77-3	8-6-36-24W4	2920	110		Testhole	
90	11-6-36-24W4	2925	62	42 - 62	Domestic stock	24 2901
91	14-6-36-24W4	2950	93	70 - 93	Domestic	70

Depth to Bedrock Elev. (feet)	Type of Well	Lithology of Aquifer	Available Drawdown (feet)	T (igpd/ft.) and K (igpd/ft.^{2})	Q_{20} (igpm)	Other Remarks
						E-Log available 600′+
						E-Log available 300′+
55 3120	Bedrock	Sandstone, Shale	80	? 500 (K = 42)	20	
45 3030	Bedrock	Fractured Siltstone, Shale, coal	115	25 (K = 2.5)	1	
24 3126	Bedrock	Sandstone	15+	14,250 (K = 356)	100	
18 3082	Bedrock	Sandstone	90+	140 (K = 4.7)	6	
15 3085	Bedrock	Sandstone Siltstone Shale, coal	90+	70 (K = 3.5)	3	Recovery data
	Bedrock					Chem. analysis available
28 3007	Bedrock	Sandstone	15+	730 (K = 12)	5	
59 2866	Bedrock ?	Fractured shale	60+	3660	104	Chem. analysis available
54 2866		Sandstone				
21 2904	Bedrock	Sandstone	30	1190 (K = 24)	17	
17 2933	Bedrock	Sandstone shale	15	1560 (K = 30)	11	

Index Number	Location	Elevation (map) In feet a.m.s.l.	Depth of Well (ft.)	Construction, Depth Interval Open to Aquifers (feet)	Use	Depth to Water Elev. (feet)
						2880
92	16-6-36-24W4	2925	90	76 - 90	Domestic	17 2908
93	16-5-36-24W4	3010	130	120 - 130	Industrial	60 2950
94	16-6-36-24W4	2925	71	60 - 71	Domestic	30 2895
95	16-6-36-24W4	2925	81	61 - 81	Domestic	17 2908
96	16-6-36-24W4	2925	50	40 - 50	Domestic	5 2920
97	16-6-36-24W4	2925	87	80 - 87	Domestic	20 2905
98	16-6-36-24W4	2925	75	55 - 75	Domestic	21 2904
99	7-7-36-24W4	2965			Domestic	
100	5-9-36-24W4	2985	60	48 - 60	Domestic	30 2955
101	5-9-36-24W4	2985	74	44 - 74	Domestic stock	32 2953
102	8-10-36-24W4	3090	100		Domestic	90 3000
103	13-11-36-24W4	3060	140	103 - 140	Domestic stock	34 3026
104	5-12-36-24W4	3040	80		Domestic stock	50 2990
105	NE-12-36-24W4	3100	61	34 - 61	Domestic stock	18 3082
106	5-14-36-24W4	3060	100			
107	3-15-36-24W4	3085	255	120 - 255	Domestic stock	78 3007
108	NW-16-36-24W4	3080	127	100 - 127	Domestic stock	99 2981
109	4-18-36-24W4	2965	108		Domestic	60 2905
110	4-18-36-24W4	2965	80	60 - 80	Domestic	42 2923

Depth to Bedrock Elev. (feet)	Type of Well	Lithology of Aquifer	Available Drawdown (feet)	T (igpd/ft.) and K (igpd/ft.^{2})	Q_{20} (igpm)	Other Remarks
59 2866	Bedrock	Sandstone	65	1220 (K = 80)	38	Chem. analysis available
60 3050	Bedrock	?	?	625 (K = 63)		
60 2865	Bedrock	Sandstone	35 +	1220 (K = 49)	20	Chem. analysis available
58 2867	Bedrock	Siltstone	55 +	>36,620	>56	
30 2895	Bedrock	Sandstone	40 +	150 (K = 15)	3	Recovery data
56 2869	Bedrock	Sandstone	60 +	1470	42	
57 2868	Bedrock	Sandstone	50 +	5707 (K = 260)	135	
						Chem. analysis available
9 2976	Bedrock	Sandstone	25 +	3120 (K = 27)	>37	Chem. analysis available
14 2971	Bedrock	Sandstone	35 +	3800 (K = 35)	>63	
18 3042	Bedrock	Sandstone shale, coals	85 ?	60 (K = 12.4)	2	Chem. analysis available
30 3070	Bedrock	Sandstone	35	910 (K = 21)	15	
						Chem. analysis available
24 3061	Bedrock	Sandstone	65 +	2980 (K = 32.4)	92	
15 3065	Bedrock	Sandstone	20 +	87,195 (K = 1744)	8.27	
						Chem. analysis available
28 2937	Bedrock	Shale, siltstone	30	6810 (K = 57)	97	Recovery data

Index Number	Location	Elevation (map) In feet a.m.s.l.	Depth of Well (ft.)	Construction, Depth Interval Open to Aquifers (feet)	Use	Depth to Water Elev. (feet)
111	12-18-36-24W4	2980	80		Domestic stock	50 2930
112	12-18-36-24W4	2980	145	117 - 145	Domestic stock	84 2896
113	NE-18-36-24W4	3030	47			40 2990
114	14-19-36-24W4	2983	60		Shothole	0 2983 +
115	14-19-36-24W4	2984	60		Shothole	0 2984 +
116	14-19-36-24W4	2983	40		Shothole	0 2983 +
117	14-19-36-24W4	2994	45		Shothole	0 2994 +
118	15-19-36-24W4	2990	60		Shothole	0 2990 +
119	16-19-36-24W4	2991	40		Shothole	0 2991 +
120	16-19-36-24W4	2997	40		Shothole	0 2997 +
121	16-19-36-24W4	2997			Shothole	0 2997 +
122	4-20-36-24W4	3035	90		Domestic	35 3000
123	12-20-36-24W4	3025	165		Domestic	60 2965
124	13-20-36-24W4	3013	47		Shothole	0 3013 +
125	NW-20-36-24W4	3025	90		Testhole	60 2965
126	5-21-36-24W4	3145	180	157 - 180	Domestic	135 3010
127	14-21-36-24W4	3165	200	130 - 200	Domestic stock	130 3135
128	4-22-36-24W4	3133	5867		Oil or gas well	
129	9-22-36-24W4	3120	130		Domestic	90 3030

Depth to Bedrock Elev. (feet)	Type of Well	Lithology of Aquifer	Available Drawdown (feet)	T (igpd/ft.) and K (igpd/ft.^{2})	Q_{20} (igpm)	Other Remarks
11 2969	Bedrock	Shale	55	2280 >19	59	Recovery data
						Chem. analysis available
						Chem. analysis available
						Chem. analysis available
						Chem. analysis available
12 3133	Bedrock	Sandstone	40+	2190 (K = 48.6)	42	
15 3150	Bedrock	Sandstone shale	65	290 K = 9.7)	9	
						E-Log available 800'+
						Chem. analysis available

Index Number	Location	Elevation (map) In feet a.m.s.l.	Depth of Well (ft.)	Construction, Depth Interval Open to Aquifers (feet)	Use	Depth to Water Elev. (feet)
130	14-22-36-24W4	3120	60			22 3098
131	4-23-36-24W4	3085	131	106 - 131	Domestic stock	72 3013
132	14-23-36-24W4	3065	62			30 3035
133	12-26-36-24W4	3060	110	79 - 110	Domestic stock	62 2998
134	4-27-36-24W4	3150	70	50 - 70	Domestic stock	46 3104
135	4-27-36-24W4	3120	62		Domestic stock	19 3101
136	4-27-36-24W4	3125	165		Abandoned	
136	4-27-36-24W4	3125	165		Abandoned	
137	9-27-36-24W4	3050	140		Domestic	
138	2-28-36-24W4	3180	300	270 - 300	Domestic stock	179.8 3000
139	2-28-36-24W4	3180	200		Domestic stock	168 3012
140	15-28-36-24W4	3090	118		Domestic stock	83 3007
141	4-29-36-24W4	3025	80		Domestic	29 2996
142	4-29-36-24W4	3030	43		Domestic	33 2997
143	3-30-36-24W4	2990	50		Stock	0 2990 +
144	8-30-36-24W4	3050	125		Domestic stock	55 2995
145	8-30-36-24W4	3050	62		Domestic stock	38 3012
146	1-31-36-24W4	3135	198	178 - 198	Domestic	151 2984
147	1-31-36-24W4	3135	206	180 - 206	Domestic	154 2981

Depth to Bedrock Elev. (feet)	Type of Well	Lithology of Aquifer	Available Drawdown (feet)	T (igpd/ft.) and K (igpd/ft.^{2})	Q$_{20}$ (igpm)	Other Remarks
35 3050	Bedrock	Sandstone	50	1230 (K = 23.7)	29	Recovery data
45 3015	Bedrock	Sandstone siltstone	40	28,670 (K = 956)	544	
17 3133	Bedrock	Sandstone	15	9490 (K = 431)	68	
50 3070	Bedrock	Sandstone	30	2440 (K = 407)	35	
60 3065	Bedrock	Shale				
60 3065	Bedrock	Shale				
						Chem. analysis available
15 3165	Bedrock	Sandstone	115	2300 (K = 66)	125	Recovery data
						Chem. analysis available
44 2981						
40 2950	Bedrock	Fractured shale				
45 3005	Bedrock	Sandstone	60	370 (K = 14.9)	11	
19 3116	Bedrock	Sandstone	40+	13,080 (K = 248)	248	
20 3115	Bedrock	Sandstone	40+	19,620 (K = 192)	372	

Index Number	Location	Elevation (map) In feet a.m.s.l.	Depth of Well (ft.)	Construction, Depth Interval Open to Aquifers (feet)	Use	Depth to Water Elev. (feet)
148	8-32-36-24W4	3110	200	130 - 200	Stock	120 2990
149	9-32-36-24W4	3100	145			125 2975
150	7-33-36-24W4	3060	122			90 2970
151	12-33-36-24W4	3075	130	90 - 130	Domestic	91 2984
152	12-33-36-24W4	3075	126			30 3045
153	16-33-36-24W4	3040	105	91 - 105	Stock	70 2970
154	13-34-36-24W4	3025	80			64 2961
154.5	4-2-36-25W4	3100	43	24 - 43	Stock	18 3087
155	2-3-36-24W4	3085	123	32 - 123	Stock	30 3055
156	2-3-36-25W4	3100	74			22 3078
157	NE-4-36-25W4	3160	120	103 - 120	Stock	63 3097
158	12-5-36-25W4	3165	200	160 - 200	Domestic stock	126 3039
159	12-6-36-25W4	3080	80			66 3014
160	8-7-36-25W4	3175	118	103 - 118	Domestic stock	55 3120
161	SW-8-36-25W4	3185	99			40 3145
162	16-8-36-25W4	3275	155	133 - 155	Domestic stock	110 3165
163	16-8-36-25W4	3275	115			
164	16-8-36-25W4	3275	109			100 3175
165	5-9-36-25W4	3225	180	120 - 180	Domestic stock	91 3134

Depth to Bedrock Elev. (feet)	Type of Well	Lithology of Aquifer	Available Drawdown (feet)	T (igpd/ft.) and K (igpd/ft.^{2})	Q_{20} (igpm)	Other Remarks
59 3051	Bedrock	Sandstone shale	70	200 (K = 2.9)	7	Recovery data Chem. analysis available
45 3030	Bedrock	Sandstone	35	5810 (K = 194)	96	Recovery data
50 2990	Bedrock	Sandstone shale	30	730 (K = 12)	10	
19 3081	Bedrock	Sandstone shale	20	190 (K = 46.8)	2	
28 3057	Bedrock	Sandstone	20	12,150 (K = 347)	115	Chem. analysis available
						Chem. analysis available
76 3084	Bedrock	Sandstone	50	950 (K = 36.4)	23	
100 3065	Bedrock	Sandstone coal, shale	60	300 (K = 15)	9	
84 3091	Bedrock	Sandstone shale	55	5890 (K = 131)	154	
68 3207	Bedrock	Shale Siltstone?	40	130 (K = 6.5)	3	Recovery data
						Chem. analysis available
						Chem. analysis available
26 3199	Bedrock	Shale Siltstone	80	80 (K = 1.4)	3	Recovery data

Index Number	Location	Elevation (map) In feet a.m.s.l.	Depth of Well (ft.)	Construction, Depth Interval Open to Aquifers (feet)	Use	Depth to Water Elev. (feet)
166	8-9-36-25W4	3175	54		Stock	8 3167
167	9-9-36-25W4	3135	145	138 - 145	Stock	<93 3042
168	12-9-36-25W4	3225	111			35 3190
169	15-10-36-25W4	3023	60		Shothole	0 3023+
170	1-12-36-25W4	2950	92		Domestic	
171	1-12-36-25W4	2950	110		Domestic	43 2907
172	1-12-36-26W4	2950	71	63 - 71	Domestic	34 2916
173	3-12-36-25W4	2970	50	38 - 50	Stock	0 2970
174	8-12-36-25W4	2960	107	80 - 107	Domestic	43 2917
175	14-12-36-25W4	2965	107	95 - 107	Domestic	45 2920
176	14-12-36-25W4	2945	155	93 - 155	Domestic	59 2886
177	14-12-36-25W4	2945	102	98 - 102	Domestic	55 2800
178	1-13-36-25W4	2925	100		Domestic	64 2861
179	1-13-36-25W4	2925	80	59 - 80	Domestic	36 2889
180	1-13-36-25W4	2925	93		Domestic	15 2910
181	1-13-36-25W4	2925	98	88 - 98	Domestic	55 2870
182	6-13-36-25W4	2925	180	172 - 180	Domestic	36 2889
183	6-13-36-25W4	2920	80	60 - 80	Domestic	13 2907
184	13-14-36-25W4	3025	75		Domestic	12 3013

Depth to Bedrock Elev. (feet)	Type of Well	Lithology of Aquifer	Available Drawdown (feet)	T (igpd/ft.) and K (igpd/ft.^{2})	Q_{20} (igpm)	Other Remarks
25 3150	Bedrock	Shale Fractured ?	40	1470 (K = 49)	28	
70 3065	Bedrock	Sandstone	?	2680 (K = 72)	38	
						Chem. analysis available
						Chem. analysis available
20 2930	Bedrock	Sandstone	30	930 (K = 23)	13	Chem. analysis available
30 2940	Bedrock	Sandstone	45+			Chem. analysis available
38 2922	Bedrock	Sandstone	55+	290 (K = 4.8)	8	
26 2939	Bedrock	Sandstone	55+	3180 (K =32)	83	
37 2908	Bedrock	Sandstone	90+	1820 (K = 30)	78	Chem. analysis available Recovery data
45 2900	Bedrock	Shale	40	3180	60	
						Chem. analysis available
37 2888	Bedrock	Sandstone	35	53,860 (K = 1077)	893	
						Chem. analysis available
25 2900	Bedrock	Shale (fractured)	35	2930 (K = 58.7)	49	Chem. analysis available
75 2850	Bedrock	Shale (Fractured)	135	340 (K = 6.8)	22	
54 2866	Bedrock	Shale, coal	50+	? 11750 (K = 1175)	278	

Index Number	Location	Elevation (map) In feet a.m.s.l.	Depth of Well (ft.)	Construction, Depth Interval Open to Aquifers (feet)	Use	Depth to Water Elev. (feet)
185	5-15-36-25W4	3095	100	80 - 100	Stock	50 3045
186	3-16-36-25W4	3190	63	49 - 63	Domestic stock	28 3162
187	16-17-36-25W4	3160	85	35 - 85	Stock	59 3101
188	12-19-36-25W4	3200	180			?
189	12-19-36-25W4	3200	185			90 3110
190	12-19-36-25W4	3200	126		Domestic	81 3119
191	11-21-36-25W4	3090			Shothole	0 3090 +
192	12-21-36-25W4	3100			Shothole	0 3100 +
193	12-21-36-25W4	3100	75		Shothole	0 3100 +
194	8-22-36-25W4	3035	105	90 - 105	Domestic stock	62 2973
195	8-22-36-25W4	3000	122		Domestic stock	30 2970
196	11-22-36-25W4	3025	190	153 - 190	Domestic stock	79 2946
197	16-22-36-25W4	3025	95	75 - 95	Domestic	40 2985
198	16-22-36-25W4	3015	94		Domestic	29 2986
R.C.A. #77-1	16-22-36-25W4	2920	120		Testhole	0 2920
199	16-22-36-25W4	2935	190	145 - 190	Domestic	15 2920
200	4-23-36-25W4	3000	165	80 - 165	Domestic	40 2960
201	14-23-36-25W4	2930	83	65 - 83	Domestic	0 2930 +

Depth to Bedrock Elev. (feet)	Type of Well	Lithology of Aquifer	Available Drawdown (feet)	T (igpd/ft.) and K (igpd/ft.^{2})	Q_{20} (igpm)	Other Remarks
39 3056	Bedrock	Siltstone shale	45+		>11	Chem. analysis available
16 3174	Bedrock	Sandstone	25+	1720 (K = 23)	20	
23 3137	Bedrock	Sandstone Shale	10	210 (K = 13)	2	Recovery data
						Chem. analysis available
	Drift					Chem. analysis available
53 2982	Bedrock	Siltstone (fractured)	35	160 (K = 11.4)	3	Recovery data Chem. analysis available
						Chem. analysis available
20 3005	Bedrock	Siltstone sandstone	105	42 (K = 1.1)	2	Chem. analysis available
23 3002	Bedrock	Sandstone shale (fractured)				Chem. analysis available
						Chem. analysis available
112 2808	Bedrock	Sand sandstone	115			
142 2793	Bedrock	Shale (fractured)	150+	50 (K = 1)	4	Recovery data Chem. analysis available
<75	Bedrock	Coal, shale	120	1470	83	Chem. analysis available
62 2868	Bedrock	Shale siltstone ?	75+	840 (K = 42)	30	Recovery data Chem. analysis available

Index Number	Location	Elevation (map) In feet a.m.s.l.	Depth of Well (ft.)	Construction, Depth Interval Open to Aquifers (feet)	Use	Depth to Water Elev. (feet)
202	14-23-36-25W4	2930	85	78 - 85	Domestic	0 2930 +
203	2-24-36-25W4	2925	60	46 - 60	Domestic	2 ? 2923
204	2-24-36-25W4	2960	100		Domestic	60 ? 2900
205	2-24-36-25W4	2945	90	70 - 90	Domestic	21 2924
206	NW-24-36-25W4	2970	95	65 - 95	Domestic stock	38 2932
207	3-25-36-25W4	2970	85	75 - 85	Domestic stock	26 2944
208	3-25-36-25W4	2975	105	40 - 105	Stock	30 2945
209	2-26-36-25W4	2950	105		Domestic	20 2930
210	2-26-36-25W4	2960	60	59 - 60	Domestic	30 2930
211	3-26-36-25W4	2940	80	60 - 80	Domestic	13 2927
212	3-26-36-25W4	2930	55	40 - 55	Domestic	0 2930
213	10-26-36-25W4	3015	90		Domestic stock	46 2969
214	10-26-36-25W4	3015	75		Domestic stock	55 2960
215	10-26-36-25W4	3015	15		Domestic stock	10 3005
216	1-27-36-25W4	3030	122		Domestic	
217	4-28-36-25W4	3093	100		Shothole	0 3093 +
218	4-28-36-25W4	3107	100		Shothole	0 3107 +
219	13-28-36-25W4	3085	80		Domestic stock	55 3030
220	8-29-36-25W4	3067	80		Shot hole	0 3067 +

Depth to Bedrock Elev. (feet)	Type of Well	Lithology of Aquifer	Available Drawdown (feet)	T (igpd/ft.) and K (igpd/ft.^{2})	Q_{20} (igpm)	Other Remarks
75 2855	Bedrock	Fractured shale	80+		30	
40 2885	Bedrock	Sandstone	50+	3270 (K = 109)	77	Chem. analysis available
						Chem. analysis available
25 2920	Bedrock	Sandstone	70		20	Chem. analysis available
41 2929	Bedrock	Sandstone	45	3970 (K = 120)	85	
35 2935	Bedrock	Sandstone siltstone	50	3924 (K = 98)	93	Recovery data
60 ? 2915	Bedrock	Sandstone				
						Chem. analysis available
60 2900	Drift	Gravel	25	8130 (K = 1626)	96	
53 2887	Bedrock	Shale Siltstone	60	690 (K = 23)	20	Pump test data Chem. analysis available
37 2803	Bedrock	Shale Siltstone	50+	1300 (K = 81)	28	
48 2967	Bedrock	Siltstone (shale)	40	1150 (K = 29)	22	
55 2960	Bedrock	Shale	15	4400 (K = 220)	31	
						Chem. analysis available
90 2995	Drift					

Index Number	Location	Elevation (map) In feet a.m.s.l.	Depth of Well (ft.)	Construction, Depth Interval Open to Aquifers (feet)	Use	Depth to Water Elev. (feet)
221	8-29-36-25W4	3070	100		Shothole	0 3070+
222	13-29-36-25W4	3093	45		Shothole	0 3093+
223	14-29-36-25W4	3100	150		Shothole	0 3100+
224	15-29-36-25W4	3100	60		Shothole	0 3100+
225	15-29-36-25W4	3100	100		Shothole	0 3100+
226	15-30-36-25W4	3125	37	23 - 37	Domestic stock	19 3106
227	1-31-36-25W4	3160	120	110 - 120	Domestic stock	61 3099
228	5-31-36-25W4	3240	175		Domestic	110 3130
229	11-31-36-25W4	3123	50		Shothole	0 3123+
230	11-31-36-25W4	3124	50		Shothole	0 3124+
231	14-31-36-25W4	3127	45		Shothole	0 3127+
232	14-31-36-25W4	3106	100		Shothole	0 3106+
233	14-31-36-25W4	3115	?		Shothole	0 3115+
234	15-31-36-25W4	3112	50		Shothole	0 3112+
235	15-31-36-25W4	3116	50		Shothole	0 3116+
236	9-31-36-25W4	3081	100		Shothole	0 3081
237	16-31-36-25W4	3077	100		Shothole	0 3077+
238	16-31-36-25W4	3074	50		Shothole	0 3074+
239	4-32-36-25W4	3145	135	110 - 135	Domestic stock	58 3087

Depth to Bedrock Elev. (feet)	Type of Well	Lithology of Aquifer	Available Drawdown (feet)	T (igpd/ft.) and K (igpd/ft.^{2})	Q_{20} (igpm)	Other Remarks
10 3115	Bedrock	Sandstone siltstone	10	380 (K = 26)	2	
58 3102	Bedrock	Siltstone shale	50	1870 (K = 31)	44	
20 3220	Bedrock	Sandstone	60	160 (K = 33)	5	
						0 - 50 clay
						0 - 50 clay
						0 - 50 clay and rocks
						0 - 50 clay
24 3121	Bedrock	Sandstone shale	70	523 (K = 32.7)	17	Recovery data

Index Number	Location	Elevation (map) In feet a.m.s.l.	Depth of Well (ft.)	Construction, Depth Interval Open to Aquifers (feet)	Use	Depth to Water Elev. (feet)
240	13-32-36-25W4	3077	50		Shothole	0 3077 +
241	13-32-36-25W4	3067	50		Shothole	0 3067 +
242	13-32-36-25W4	3066	40		Shothole	0 3066 +
243	13-32-36-25W4	3067	150		Shothole	0 3067 +
R.C.A. #77-2	15-33-36-25W4	3125	80	50 - 80	Testhole	18 3107
244	15-34-36-25W4	2969	60		Shothole	0 2969 +
245	13-35-36-25W4	3021	52		Shothole	0 3021 +
246	15-35-36-25W4	3060	109	75 - 109	Stock	70 2990
247	15-35-36-25W4	3060	230		Stock	110 2950
248	15-35-36-25W4	3055	265		Domestic	105 2950
249	13-11-36-26W4	3125	121		Stock	45 3080
250	1-14-36-26W4	3070	60		Domestic	25 3045
251	12-14-36-26W4	3150	80	70 - 80	Domestic	28 3122
252	12-14-36-26W4	3160	102		Domestic	50 3110
253	15-13-36-26W4	3120	75		Shothole	0 3120 +
254	2-23-36-26W4	3079	75		Shothole	0 3079 +
255	2-23-36-26W4	3115	75		Shothole	0 3115 +
256	2-23-36-26W4	3115	75		Shothole	0 3115 +
257	10-23-36-26W4	3117	75		Shothole	0 3117 +

Depth to Bedrock Elev. (feet)	Type of Well	Lithology of Aquifer	Available Drawdown (feet)	T (igpd/ft.) and K (igpd/ft.^{2})	Q_{20} (igpm)	Other Remarks
						0 - 50 clay
						0 - 50 clay
						0 - 40 clay
54 3071	Bedrock	Sandstone	45			
						0 - 60 sand & gravel
63 2997	Bedrock	Sandstone siltstone coal	30	19,620 (K = 654)	279	
38 3022	Bedrock	Sandstone	115	575 (K = 73)	31	
35 3020	Bedrock	Sandstone				
35 3090	Bedrock	Sandstone	65	13,080 (K = 409)	403	Chem. analysis available
>60	Drift	Sand gravel	30	860 (K = 86)	12	
18 3132	Bedrock	Sandstone	45	410 (K = 23)	9	

Index Number	Location	Elevation (map) In feet a.m.s.l.	Depth of Well (ft.)	Construction, Depth Interval Open to Aquifers (feet)	Use	Depth to Water Elev. (feet)
258	10-23-36-26W4	3117	75		Shothole	0 3117+
259	2-24-36-26W4	3125	50		Shothole	0 3125+
260	2-25-36-26W4	3079			Shothole	0 3079+
261	2-25-36-26W4	3115			Shothole	0 3115+
262	3-25-36-26W4	3110	60		Shothole	0 3110+
263	13-25-36-26W4	3115	30		Shothole	0 3115+
264	13-25-36-26W4	3115	60		Shothole	0 3115+
265	13-25-36-26W4	3120	75		Shothole	0 3120+
266	15-25-36-26W4	3135	45		Shothole	0 3135+
267	15-25-36-26W4	3135	75		Shothole	0 3135+
268	16-25-36-26W4	3160	140		Domestic stock	40 3120
269	16-25-36-26W4	3160	130		Domestic stock	50 3110
270	16-25-36-26W4	3160	230	177 - 230	Domestic stock	130 3030
271	8-26-36-26W4	3093	60		Shothole	0 3093+
272	13-26-36-26W4	3119	80		Shothole	0 3119+
273	13-26-36-26W4	3122	30		Shothole	0 3122+
274	16-26-36-26W4	3115	150		Shothole	0 3115+
275	1-27-36-26W4	3120	180		Shothole	0 3120+
276	9-27-36-26W4	3110	80		Shothole	0 3110+
277	10-35-36-26W4	3160	280		Domestic stock	60 3100

Depth to Bedrock Elev. (feet)	Type of Well	Lithology of Aquifer	Available Drawdown (feet)	T (igpd/ft.) and K (igpd/ft.^{2})	Q_{20} (igpm)	Other Remarks
35 3085	Bedrock	Sandstone shale				
35 3100	Bedrock	Sandstone shale				
48 3112	Bedrock	Siltstone coals	95	350 (K-27)	16	Chem. analysis available Recovery data

Index Number	Location	Elevation (map) In feet a.m.s.l.	Depth of Well (ft.)	Construction, Depth Interval Open to Aquifers (feet)	Use	Depth to Water Elev. (feet)
278	14-35-36-26W4	3130	94	82 - 94	Stock	68(?) 3062
279	SW-36-36-26W4 (6)	3190	75			30 3160
280	15-36-36-26W4	3215	125		Domestic	75 3140
281	1-4-37-24W4	3025	90	65 - 90	Domestic	60 2965
282	SE-6-37-24W4	3060	135		Stock	75 2985
283	16-7-37-24W4	2975	320	297 - 320	Domestic stock	150 2825
284	1-18-37-24W4	2930	240	200 - 240	Domestic stock	190 2740
285	1-1-37-25W4	3165	242	200 - 242	Domestic stock	140 3025
286	4-1-37-25W4	3030	70		Domestic	14 3016
287	16-2-37-25W4	3140	180		Domestic	120 3020
288	2-3-37-25W4	3000	80		Stock	0 3000+
289	9-3-37-25W4	3080	125	102 - 125	Domestic stock	105 2975
290	12-3-37-25W4	3040	110	80 - 110	Industrial	70 2970
291	9-4-37-25W4	3075	165	104 - 165	Domestic	95 2980
292	5-5-37-25W4	3070	50		Shothole	0 3070+
293	5-5-37-25W4	3090	50		Shothole	0 3090+
294	1-6-37-25W4	3074	50		Shothole	0 3074+
295	1-6-37-25W4	3075	50		Shothole	0 3075+
296	1-6-37-25W4	3082	50		Shothole	0 3082+

Depth to Bedrock Elev. (feet)	Type of Well	Lithology of Aquifer	Available Drawdown (feet)	T (igpd/ft.) and K (igpd/ft.^{2})	Q_{20} (igpm)	Other Remarks
82 3048	Bedrock	Shale (fractured?)	20	630	6	
						Chem. analysis available
65 2960	Bedrock	Sandstone	25	19,690 (K = 492)	233	
52 2923	Bedrock	Siltstone shale, coal	200	1170 (K = 20)	111	
108 2822	Bedrock	Sandstone	35	730 (K = 18.3)	12	
20 3145	Bedrock	Sandstone siltstone	23	2950 (K = 42)	32	
						Chem. analysis available
						Chem. analysis available
90 2990	Bedrock	Shale fractured	15	2625 (K = 66)	19	
45 2995	Bedrock	Siltstone	40	13,080	248	No drawdown
88 2987	Bedrock	Siltstone sandstone coal	65	13,080		No drawdown
						0 - 50 till
						0 - 50 till
						0 - 50 till
						0 - 50 till
						0 - 50 till

Index Number	Location	Elevation (map) In feet a.m.s.l.	Depth of Well (ft.)	Construction, Depth Interval Open to Aquifers (feet)	Use	Depth to Water Elev. (feet)
297	1-6-37-25W4	3076	80		Shothole	0 3076+
298	1-6-37-25W4	3067	50		Shothole	0 3067+
299	1-6-37-25W4	3082	50		Shothole	0 3082+
300	1-6-37-25W4	3086	50		Shothole	0 3086+
301	2-6-37-25W4	3078	50		Shothole	0 3078+
302	3-6-37-25W4	3100			Shothole	0 3100+
303	4-6-37-25W4	3113	50		Shothole	0 3113+
304	7-6-37-25W4	3081	50		Shothole	0 3081+
305	8-6-37-25W4	3080	55		Shothole	0 3080+
306	13-7-37-25W4	3166	60		Shothole	0 3166+
307	16-8-37-25W4	3105	150		Shothole	0 3105+
308	16-8-37-25W4	3104	62		Shothole	0 3104+
309	5-9-37-25W4	3134	50		Shothole	0 3134+
310	5-9-37-25W4	3127	50		Shothole	0 3127+
311	4-10-37-25W4	3065	100		Domestic	81 2982
312	12-14-37-25W4	3060	120	104 - 120	Stock	90 2970
313	12-14-37-25W4	3060	110		Domestic stock	90 2970
314	3-16-37-25W4	3135	200	145 - 200	Domestic	121 3014

Depth to Bedrock Elev. (feet)	Type of Well	Lithology of Aquifer	Available Drawdown (feet)	T (igpd/ft.) and K (igpd/$ft.^2$)	Q_{20} (igpm)	Other Remarks
						0 - 50 till
						0 - 50 till
						0 - 50 till
						0 - 50 till
						0 - 50 till
						0 - 50 till
						0 - 20 gravel 20-50 clay & rock
						0 - 50 clay & rock
100 2965	Drift	Drift/Bedrock Contact				Chem. analysis available
92 2968	Bedrock	Fractured shale, siltstone	25	3755 (K = 94)	45	Recovery data
	Bedrock	Shale, siltstone				Chem. analysis available
136 2999	Bedrock	Shale sandstone	70	140 (K = 7.2)	5	

Index Number	Location	Elevation (map) In feet a.m.s.l.	Depth of Well (ft.)	Construction, Depth Interval Open to Aquifers (feet)	Use	Depth to Water Elev. (feet)
315	1-17-37-25W4	3105	59		Shot hole	0 3105+
316	8-21-37-25W4	3110	212	180 - 212	Domestic stock	172 2938
317	6-24-37-25W4	2950	130	100 - 130	Domestic stock	20 2930
318	8-28-37-25W4	3025	100		Domestic	90 2935
319	4-31-37-25W4	3109	60		Shothole	0 3109+
320	14-31-37-25W4	3025	120		Stock	37 2988
321	14-31-37-25W4	3025	90			50 2975
322	16-31-37-25W4	3000	150		Stock	115 2885
323	13-32-37-25W4	2950	130	34 - 130	Domestic	53 2897
324	15-32-27-25W4	2910	90	70 - 90	Domestic	30 2880
325	1-1-37-25W4	3139	180		Shothole	0 3139+
326	4-3-37-26W4	3160	110	36 - 110	Domestic stock	37 3123
327	4-3-37-26W4	3160	50		Domestic stock	47 3113
328	8-3-37-26W4	3135	15		Stock	0 3135+
329	13-3-37-26W4	3205	140		Domestic stock	90 3115
330	16-4-37-26W4	3185	237	147 - 237	Domestic stock	124 3061
331	8-9-37-26W4	3185	270	250 - 270	Stock	224 2961
332	8-9-37-26W4	3170	382	282 - 382	Stock	185 2985

Depth to Bedrock Elev. (feet)	Type of Well	Lithology of Aquifer	Available Drawdown (feet)	T (igpd/ft.) and K (igpd/ft.^{2})	Q_{20} (igpm)	Other Remarks
164 2946	Bedrock	Sandstone siltstone	30	26,158 (K = 581)	372	
97 2853	Bedrock	Shale siltstone	100+	190 (K = 14.6)	9	Recovery data
91 2914						Chem. analysis available
35 2990	Bedrock	Sandstone	75	1010 (K = 25)	36	
16 3009	Bedrock	Sandstone shale	?			
40 2960	Bedrock	Sandstone	30+	370 (K = 7)	5	Chem. analysis available
30 2920	Bedrock	Sandstone	60	650 (K = 21.8)	19	
8 2902	Bedrock	Sandstone	55+	290 (K = 13.3)	8	
12 3148	Bedrock	Siltstone shale sandstone	65	40 (K = 3.4)	1	
	Bedrock	Siltstone shale sandstone				Chem. analysis available
90 3115	Bedrock	Siltstone shale	45	280		Chem. analysis available
10 3175	Bedrock	Sandstone siltstone	45	660 (K = 20)	14	Pump test data
23 3162	Bedrock	Siltstone shale sandstone	40	1330 (K = 16.3)	25	
42 3128	Bedrock	Sandstone coals	190	80 (K = 2)	7	

Index Number	Location	Elevation (map) In feet a.m.s.l.	Depth of Well (ft.)	Construction, Depth Interval Open to Aquifers (feet)	Use	Depth to Water Elev. (feet)
333	8-9-37-26W4	3180	240	215 - 240	Stock	179 3001
334	5-10-37-26W4	3185	185	138 - 185	Stock	137 3048
335	13-10-37-26W4	3150	140	100 - 140	Domestic	100 3050
335.5	NE-10-37-26W4	3180	90	70 - 90	Stock	41 3139
336	NW-12-37-26W4	3240	82			
337	SW-13-37-26W4	3200	125			
338	1-15-37-26W4	3165	105	90 - 105	Domestic stock	32 3133
339	3-15-37-26W4	3140	130	60 - 130	Domestic stock	95 3045
340	2-21-37-26W4	3060	84		Domestic stock	40 3020
341	4-22-37-26W4	3057	45		Shothole	0 3057 +
342	15-22-37-26W4	3160	64	57 - 64	Domestic stock	15 3145
343	1-23-37-26W4	3435	262	183 - 262	Domestic	231 3204
344	1-24-37-26W4	3440	500		Abandoned	187 3253
345	1-24-37-26W4	3440	210	200 - 210	Domestic	185 3255
346	1-24-37-26W4	3440	400		Domestic	179 3261
347	12-24-37-26W4	3300	96		Stock	46 3254
348	13-25-37-26W4	3150	80	50 - 80	Domestic	18 3112
349	NE-25-37-26W4	3190	98		Domestic	6 3184

Depth to Bedrock Elev. (feet)	Type of Well	Lithology of Aquifer	Available Drawdown (feet)	T (igpd/ft.) and K (igpd/ft.^{2})	Q_{20} (igpm)	Other Remarks
27 3153	Bedrock	Sandstone	55	820 (K = 41)	21	
12 3173	Bedrock	Fractured shale sandstone	40	760 (K = 15)	14	Recovery data
22 3138	Bedrock	Siltstone sandstone	35	700 (K = 12)	12	
70 3120	Bedrock	Shale Siltstone	40	3860 (K = 97)	73	Pump test data
						Chem. analysis available
						Chem. analysis available
85 3080	Bedrock	Shale Siltstone	65	560 (K = 16)	17	
22 3118	Bedrock	Sandstone	30	13,080 (K = 654)	186	
70 2990	Bedrock	Sandstone	40+			
						0 - 45 clay
						Chem analysis available
40 3395	Bedrock	Shale Sandstone	30	980 (K = 38)	2	Pump test data
43 3397	Bedrock	Siltstone shale sandstone	13	290 (K = 38)	2	
43 3397	Bedrock	Sandstone	9	8890 (K = 444)	38	
	Bedrock	Sandstone siltstone	20	500 (K = 23)	5	Pump test data
18 3132	Bedrock	Fractured shale siltstone	25	2430 (K = 122)	29	
						Chem. analysis available

Index Number	Location	Elevation (map) In feet a.m.s.l.	Depth of Well (ft.)	Construction, Depth Interval Open to Aquifers (feet)	Use	Depth to Water Elev. (feet)
350	3-27-37-26W4	3125	33			12 3113
351	1-34-37-26W4	3079	60		Shothole	0 3079+
352	8-34-37-26W4	3085	90		Stock	32 3053
353	1-35-37-26W4	3105	150		Shothole	0 3105+
354	NE-35-37-26W4	2985	151	118 - 151	Stock	99 2886
355	8-36-37-26W4	3100	76	61 - 76	Stock	27 3073
356	8-36-37-26W4	3100	120	90 - 120	Stock	50 3050
357	8-36-37-26W4	3100	85			0 3100+
358	14-36-37-26W4	3030	140	58 - 140	Domestic stock	67 2963
359	14-36-37-26W4	3030	130	60 - 130	Domestic stock	75 2955
L-1	SE-14-35-25W4	3142	120		Domestic stock	
L-2	NE-20-35-25W4	3145	145		Domestic stock	
L-3	SW-28-35-25W4	3125	22	Dug	Domestic stock	18 3107
L-4	SE-30-35-25W4	3080	111		Domestic stock	90 2990
L-5	SE-34-35-25W4	3090	136		Domestic stock	
L-6	NW-34-35-25W4	3175	101		Domestic stock	40 3135
L-7	SW-36-35-25W4	2945	0		Spring	0 2945+
L-8	NW-4-36-25W4	3260	85		Domestic stock	

Depth to Bedrock Elev. (feet)	Type of Well	Lithology of Aquifer	Available Drawdown (feet)	T (igpd/ft.) and K (igpd/ft.^{2})	Q_{20} (igpm)	Other Remarks
	Drift					
65 3020	Bedrock	Sandstone shale	50	3667 (K = 122)	87	
63 2922	Bedrock	Sandstone	45	500 (K = 39)	11	
59 3041	Bedrock	Fractured shale	40	13,730 (K = 549)	260	
87 3013	Bedrock	Sandstone siltstone	60	1635 (K = 41)	47	Chem. analysis available
43 2987	Bedrock	Siltstone shale sandstone	40	1510 (K = 28)	29	
42 2988	Bedrock	Shale sandstone coal	15	4670 (K = 104)	33	
60 3082	Bedrock					
95 3050	Bedrock					
	Drift					
85 2995	Bedrock					
	Bedrock					
	Bedrock					
	Drift					
	Bedrock					

Index Number	Location	Elevation (map) In feet a.m.s.l.	Depth of Well (ft.)	Construction, Depth Interval Open to Aquifers (feet)	Use	Depth to Water Elev. (feet)
L-9	NE-11-36-25W4	2990	86		Domestic stock	46 2944
L-10	SW-27-36-25W4	3032	14	Dug	Domestic stock	10 3022
L-11	SE-28-36-25W4	3045	35	Dug	Domestic stock	30 3015
L-12	SW-28-36-25W4	3090	180		Domestic stock	
L-13	SW-30-36-25W4	3190	120		Domestic stock	45 3145
L-14	NW-30-36-25W4	3190	60		Domestic stock	50 3140
L-15	NE-12-36-26W4	3090	24	Dug	Domestic stock	23 3067
L-16	NW-13-36-26W4	3085	130		Domestic stock	
L-17	NW-23-36-26W4	3150	120		Domestic stock	10 3140
L-18	SW-25-36-26W4	3124	75		Domestic stock	20 3104
L-19	NE-26-36-26W4	3105	60		Domestic stock	4 3101
L-20	SE-36-36-26W4	3237	64		Domestic stock	40 3197
L-21	NW-1-37-25W4	3122	20	Dug	Domestic stock	<20
L-22	NE-3-37-25W4	3080	115		Domestic stock	85 2995
L-23	SW-6-37-25W4	3153	36	Dug	Domestic stock	+2 3155
L-24	SW-10-37-25W4	3065	100		Domestic stock	
L-25	NW-23-37-25W4	3003	25	Dug	Domestic stock	<25
L-26	SE-28-37-25W4	3033	108		Domestic stock	78 2955

Depth to Bedrock Elev. (feet)	Type of Well	Lithology of Aquifer	Available Drawdown (feet)	T (igpd/ft.) and K (igpd/ft.^{2})	Q_{20} (igpm)	Other Remarks
40 2950	Bedrock					
	Drift					
	Drift					
	Bedrock					
100 3090	Bedrock					
	Drift					
	Drift					
	Bedrock					
50 3100	Bedrock					
60 3064	Bedrock					
60+	Drift	Gravel				
	Bedrock					
>70	Drift					
90 2990	Bedrock					
	Drift					
100 2965	Drift					
>25	Drift					
91 2942	Bedrock					
	Drift					

Index Number	Location	Elevation (map) In feet a.m.s.l.	Depth of Well (ft.)	Construction, Depth Interval Open to Aquifers (feet)	Use	Depth to Water Elev. (feet)
L-27	SW-2-37-26W4	3152	0		Spring	0 3152+
L-28	NE-10-37-26W4	3180	65		Domestic stock	25 3155
L-29	NW-24-37-26W4	3339	74		Domestic stock	
L-30	NE-26-37-26W4	3110	98		Domestic stock	6 3104
L-31	SW-35-37-26W4	3072	100		Domestic stock	25 3047

Depth to Bedrock Elev. (feet)	Type of Well	Lithology of Aquifer	Available Drawdown (feet)	T (Igpd/ft.) and K (Igpd/ft.^{2})	Q_{20} (igpm)	Other Remarks
>65	Drift					
10 3329	Bedrock					
85 3025	Bedrock					
	Bedrock					

APPENDIX B: Hydrochemical Analyses

Notes to Appendix B

1. Column 3: TDS = total dissolved solids as determined by weighing the residue on drying.
2. Columns 3 to 12: epm = equivalents per million, and the symbol % = percentage epm of the ion to the total respective cations or anions.
3. Columns 3 and 4: When the entry Ca^{+} Mg$^{=}$ is present, this indicates that these constituents were estimated from the reported "hardness" and not determined individually.
4. Columns 14 and 15: ppm = parts per million concentrations.
5. Column 16: Facies type refers to the classification (figures 41 and 42) given in the text.

Index Number	Well Depth Date Sampled (feet)	TDS ppm	Na		K		Ca		Mg		Na + K	
			epm	%	epm	%	epm	%	epm	%	epm	%
2	75 13-12-76	1071	12.53	65.8	0.09	0.47	3.14	16.5	3.29	17.3	12.62	66.3
4	108 17-2-60	736					10.58	Ca +	Mg = 97.0		0.32	3
5	190 21-6-77	2145	22.23	61.2	0.10	0.3	7.24	20.0	6.58	18.1	22.33	61.5
9	252 10-8-60	1026					8.98	Ca +	Mg = 65.6		4.71	34.4
12	300 2-6-64	782					0.2	Ca +	Mg = 1.4		13.85	98.6
13	230 12-4-61	1510					10.58	Ca +	Mg = 49.4		10.66	49.8
14	215 8-1-68	1676	7.39	60.8			4.77	Ca +	Mg = 39.2			
16	266 7-5-74	1229	5.61	26.9	0.4	0.2	8.48	40.6	6.74	32.3	5.65	27.0
18	118 26-6-73	1090	11.31	76.1	0.6	0.4	1.85	12.4	1.65	11.1	11.37	76.5
19	90 3-9-72	517	1.05	10.8	0.10	1.0	4.59	47.0	4.03	41.3	1.15	11.8
22	80 19-5-77	642	2.92	26.5	0.11	1.0	3.49	31.7	4.44	40.3	3.03	27.5
25	58 20-10-65	844					4.19	Ca +	Mg = 30.0		9.77	70.0
26	132 30-8-68	886	12.18	76.7			3.57	Ca +	Mg = 2.25			
33	158 7-10-69	1130					5.21	Ca +	Mg = 67		7.53	33
34	81 18-8-72	1380					1.35	6.74	2.14	10.7	16.53	83
37	110 31-3-61	1178					4.59	Ca +	Mg = 24		14.60	76
38	50 15-9-77	544	1.13	11.6	.10	1.0	4.39	45.1	4.11	42.2	1.23	12.6
40	96 7-1-68	1332	14.53	89.5			1.7	Ca +	Mg = 10.5			
41	80 7-1-68	886	18.5	98.5			.28	Ca +	Mg = 1.5			

Ca/Mg ratio	Cl epm	Cl %	SO_4 epm	SO_4 %	$HC0_3 + CO_3$ epm	$HC0_3 + CO_3$ %	NO_3 epm	NO_3 %	Fe ppm	F ppm	Facies Type
0.95	0.06	0.3	6.83	37.0	11.57	62.7	Tr.		0.28	0.43	1
			2.52	23.1	8.26	75.8	0.12	1.1			2
1.10	0.09	0.3	21.28	62.5	12.65	37.1	Tr.		4.71	0.92	3
	0.11	0.8	6.79	49.6	6.79	49.6			0.4		4
	0.62	4.4	0.15	1.1	13.28	94.5					1
	0.06	0.1	11.03	51.5	10.33	48.2			5.0	0.20	4
	0.17	0.7	16.66	64.6	8.95	14.7	0.05	0.1	0.10	0.66	3
1.26	0.11	0.5	11.9	57.0	8.87	42.5	Tr.		0.50	0.48	4
1.12	0.03	0.2	2.23	17.0	10.83	82.7	Tr.		Tr.		1
1.14	0.05	0.50	1.66	16.8	8.14	82.5	0.11	1.1		0.15	2
0.79	0.06	0.50	1.48	27.9	8.62	69.1	0.32	2.6	0.07	0.12	2
			3.73	26.7	10.23	73.3					1
	.06	0.41	4.13	28.1	10.52	71.5			3.52		1
	.11	0.5	7.85	34.5	13.47	59.2			36.5		4
0.63	0.9	0.5	9.27	46.3	10.66	53.2	Tr.		0.2		3
	.06	0.3	8.06	42.1	11.07	57.9			2.23		3
1.07	.31	3.1	2.48	24.9	6.11	61.5	1.04	10.5	0.16	0.11	2
	.06	0.3	9.02	47.1	10.03	52.4	.03	0.2	0.03	0.76	3
	.11	0.75	3.58	24.5	10.92	74.7			0.27	1.27	1

Index Number	Well Depth Date Sampled (feet)	TDS ppm	Na epm	Na %	K epm	K %	Ca epm	Ca %	Mg epm	Mg %	Na + K epm	Na + K %
46	215 7-1-68	702					7.37	Ca +	Mg = 65.2		3.93	34.8
48	SPRING 31-1-61	1280					11.88	Ca +	Mg = 63		6.88	37
52	115 2-3-77	1743	25.8	93.7	.25	0.9	1.15	4.2	.33	1.2	26.05	94.6
54	150 26-8-74	633	7.74	67.8	.07	0.6	1.3	11.4	2.3	20.2	7.81	68.5
58	290 21-4-60	748										
59	102 16-8-72	428					1.60	25.9		7.9	4.09	92.1
60	60 5-4-77	204	1.61	35.1	.097	2.1	1.15	25.1	1.73	37.7	1.71	37.2
61	125 30-10-75	710	14.14	99.5	.064	0.5	0.05		0.08		14.2	100.0
66	130 21-9-75	893	12.44	95.8	.008	0.06	0.45	3.5	0.08	0.62	12.45	95.9
67	120 18-11-75	1585	21.49	92.4	.05	0.2	1.30	5.6	0.41	1.8	21.54	92.7
68	132 18-9-60	1356					3.0	Ca +	Mg = 14.0		18.32	86.0
69	183 -7-70	804					1.76	Ca +	Mg = 14.0		11.03	86.0
84	257 -5-68	792					0.28	Ca +	Mg = 2.1		12.91	97.0
88	65 23-8-76	366	0.87	13.0	.08	1.2	4.89	73.3	0.82	12.3	.95	14.2
90	62 -8-71	920					0.35	2.2	1.65	10.6	13.64	87.0
92	90 20-9-76	373	1.39	18.8	.09	1.2	3.09	41.8	2.8	37.9	1.48	20.0
94	71 2-6-74	306	.48	7.7	.067	1.1	2.5	39.9	3.21	51.3	.55	8.8
99	-6-68	526					2.36	Ca +	Mg = 25.0		7.0	75.0
100	60	344					3.81	Ca +	Mg = 69.0		1.73	31.0

Ca/Mg	Cl		SO$_4$		HC0$_3$ + CO$_3$		NO$_3$		Fe	F	Facies
ratio	epm	%	epm	%	epm	%	epm	%	ppm	ppm	Type
	.06	0.53	2.98	26.4	8.26	73.1			0.40	0.23	2
	.09	0.5	8.25	41.0	10.42	55.5	Tr.		0.80		4
3.49	.14	0.5	15.57	56.2	11.98	43.3	Tr.		0.12	0.47	3
0.57	.11	0.97	2.94	25.9	8.31	73.2	Tr.		Tr.	0.19	1
			2.58	22	9.44	78			0.30		
3.27	0.03	0.5	1.06	17.2	5.08	82.3	0.01			0.1	1
0.67	0.11	2.9	0.2	5.2	3.51	91.9	Tr.		3.44	0.12	2
	Tr.		0.81	7.0	10.7	92.7	Tr.		0.80	0.47	1
	0.40	2.5	6.20	38.4	9.51	58.9	0.02	0.10	0.10	0.91	3
3.17	.03	0.1	14.8	56.1	11.54	43.8	Tr.		0.10	0.93	3
	.17	0.8	9.91	46.5	11.24	52.7			0.12		3
	.06	0.5	4.62	36.1	8.06	63.0	Tr.		0.40		1
	.06	0.5	3.03	22.9	10.13	76.2			3.18	1.23	1
5.96	Tr.		0.67	9.0	5.75	90.9	Tr.		0.40	0.13	2
0.21	.09	0.6	5.21	33.3	10.33	66.1	.008	.05			1
1.10	.03	0.37	.21	2.6	7.98	97.1	Tr.		0.60	0.13	2
0.78	.23	3.7	.58	9.3	5.43	86.9	Tr.		0.20	0.20	2
	0.11	1.2	2.12	22.7	7.12	76.2			0.6		1
	0.11	2.0	0.42	7.6	5.00	90.3			1.01	0.16	2

Index Number	Well Depth Date Sampled (feet)	TDS ppm	Na epm	Na %	K epm	K %	Ca epm	Ca %	Mg epm	Mg %	Na + K epm	Na + K %
	-6-68											
103	140 28-5-76	867	13.31	96.4	0.02	.15	0.4	2.9	0.08	.6	13.33	96.6
106	100 -5-68	874					3.11	Ca +	Mg = 22.0		10.76	78.0
109	108 8-6-77	360	2.83	41.0	0.08	1.2	1.70	24.6	2.30	33.3	2.91	42.2
113	47 -5-61	1224	13.31	81.7			2.99	Ca +	Mg = 18.3			
122	90 -9-59	396					5.79	Ca +	Mg = 90.0		0.67	10.0
123	165 -5-68	840	14.35	99.5			0.08	Ca +	Mg = 0.5		0.17	1.3
125	90 -5-68	546					7.58	Ca +	Mg = 29.0		6.39	71.0
129	130 -9-68	828					8.60	Ca +	Mg = 53.0		7.7	47.0
137	140 -5-68	1528	22.75	98.9			0.26	Ca +	Mg = 1.1			
139	200	816	14.72	97.4			0.40	Ca +	Mg = 2.6			
148	200 -5-68	1784					0.62	Ca +	Mg = 2.4		25.64	97.6
155	123 -8-62	986					3.71	Ca +	Mg = 23.3		12.22	76.7
156	74 20-4-60	874					5.79	Ca +	Mg = 40.1		8.58	59.5
170	92 29-5-77	884	14.66	97.6	0.03	0.2	0.25	1.7	0.08	0.05	14.69	97.8
171	110 21-5-73	1088	9.79	76.8	0.069	0.54	2.30	18.1	0.49	3.85	9.86	77.4
172	71 23-7-70	1020					2.30	Ca +	Mg = 13.9		14.17	85.8
173	50 6-6-74	1046	13.75	78.2	0.09	0.5	1.75	9.95	1.97	11.2	13.84	78.7
176	155 9-8-76	687	14.83	97.3	0.03	0.2	0.30	1.97	0.08	0.5	14.86	97.5
178	100 15-5-77	375	1.00	12.3	0.07	0.9	3.64	44.9	3.37	41.6	1.07	13.2

Ca/Mg	Cl		SO$_4$		HC0$_3$ + CO$_3$		NO$_3$		Fe	F	Facies
ratio	epm	%	epm%		epm	%	epm	%	ppm	ppm	Type
	0.03	0.2	5.81	38.9	9.10	60.9	Tr.		0.30	1.30	1
	0.06	0.4	4.96	35.8	8.85	63.8			0.77	0.16	1
0.74	0.14	2.0	0.67	9.3	6.38	88.7	Tr.		0.28	0.08	2
	0.11	0.6	7.5	40.7	10.62	57.7					3
					6.46	99.0	.021		0.40		1
	0.17	1.3	4.64	35.2	8.36	63.5				1.00	1
	0.40	4.5	2.46	27.4	6.10	68.0	.01	0.1	0.06	0.16	1
	0.17	1.0	5.21	32.0	10.42	63.9			14.0		2
	0.06	0.3	10.56	44.0	13.37	55.7			0.06	0.66	3
	0.06	0.9	3.91	56.5	2.95	42.6			0.60		3
	0.06	0.2	14.10	53.7	12.10	46.1			0.02	0.90	3
	0.11	0.7	6.06	38.0	9.74	61.1			1.15	0.45	1
			3.91		10.52				1.7		2
3.13	0.03		4.56	29.8	10.72	70.0	Tr.		0.08	0.68	1
4.69	0.09	0.6	3.75	26.7	10.18	72.6	Tr.		2.4	0.23	1
	0.06	0.4	5.50	33.3	10.96	66.3			1.36		1
0.89	.11	0.6	6.25	34.2	11.90	65.1	Tr.		0.70	0.52	1
3.75	0.09	0.8	0.21	1.9	10.80	96.7	Tr.		Tr	1.15	1
1.08	0.14	1.9	0.65	8.7	6.69	89.4	Tr.		0.58	0.08	2

Index Number	Well Depth Date Sampled (feet)	TDS ppm	Na epm	Na %	K epm	K %	Ca epm	Ca %	Mg epm	Mg %	Na + K epm	Na + K %
180	93 27-7-75	540	7.92	81.4	0.05	0.5	1.25	12.9	0.49	5.0	7.97	81.9
181	98 10-9-73	513	8.7	94.7	0.21	2.3	0.20	2.2	0.08	0.9	8.91	97.0
185	100 18-12-61	916					3.29	Ca +	Mg = 26.1		9.29	73.9
188	180 8-1-68	892	18.17	98.9			0.20	Ca +	Mg = 1.1			98.9
189	185 -4-64	1802					15.77	Ca +	Mg = 68.5		7.09	30.8
194	105 -70	790	17.07	97.5			0.42	Ca +	Mg = 2.4			97.5
195	122 -2-61	666	14.66	96.7			0.50	Ca +	Mg = 3.3			
196	190 -8-75	611	10.75	98.4	0.015	0.14	0.05	0.5	0.08	0.7	10.77	98.5
197	95 11-8-71	510					1.35	18.2	2.88	38.8	3.2	43.1
198	94 30-6-65	494					6.49	Ca +	Mg = 81.8		1.44	18.2
199	190 2-8-77	818	13.40	88.9	0.077	0.5	1.0	6.6	0.58	3.9	13.48	89.4
200	165 -2-61	520					4.99	Ca +	Mg = 55.0		4.10	45.0
201	83	9.15					0.30	2.1	0.41	2.9	13.31	94.7
203	60 -9-75	539	9.05	96.5	0.02	0.21	0.20	2.1	0.08	0.9	9.07	96.7
204	100 14-2-75	528	9.09	93.1	0.03	0.31	0.55	5.6	0.082	0.8	9.12	93.4
205	90 27-7-76	619	8.18	80.8	0.06	0.6	0.65	6.4	1.23	12.1	8.24	81.3
209	105 -6-75	856	14.40	97.5	0.02	0.14	0.25	1.7	0.082	0.56	14.42	97.6
211	80 28-7-75	910	16.01	97.7	0.03	0.18	0.25	1.5	0.082	0.5	16.04	97.9
216	122 -8-65	750					2.79	Ca +	Mg = 22.4		9.49	76.2

Ca/Mg ratio	Cl epm	Cl %	SO_4 epm	SO_4 %	$HC0_3$ + CO_3 epm	$HC0_3$ + CO_3 %	NO_3 epm	NO_3 %	Fe ppm	F ppm	Facies Type
2.55	0.06	0.6	0.29	2.8	10.08	96.2	Tr.		0.60	1.01	1
2.5	0.028	0.3	1.21	13.4	7.75	86.0	Tr.		0.10	0.50	1
	0.028	0.2	8.20	65.2	4.33	34.4	Tr.		0.20	0.34	3
	0.06	0.4	4.02	27.2	10.64	72.0			0.08	1.11	1
			13.39		9.64				4.80		4
	0.06	0.5	2.46	19.3	10.23	80.2			0.24		1
	Tr.		1.94	17.8	8.95	82.2			0.20		1
	0.20	1.7	1.00	8.4	10.25	86.1	Tr.		0.90	8.75	1
0.47	0.09	1.2	0.63	8.5	6.69	90.0	0.0	0.2			2
		0.98		126.88 .4		860.07 .8	0. 9		Tr.		2
1.72	3.86	24.8	0.21	1.4	11.43	73.6	Tr.		0.76	0.68	1
	0.06	0.7	0.90	9.9	8.16	89.5			0.80		2
0.73	0.06	0.4	4.16	29.6	9.83	70.0	Tr.		0.90		1
2.5	0.14	1.5	2.35	25.2	6.68	71.6	Tr.		0.90	3.00	1
6.71	0.028	0.3	1.58	17.5	7.41	81.9	Tr.		0.30	0.51	1
0.53	0.06	0.5	2.50	21.1	9.27	78.1	Tr.		0.40	0.74	1
3.05	0.14	1.0	5.95	43.9	7.38	54.5	Tr.		0.40	1.23	3
3.05	0.028	0.2	4.62	30.8	10.3	68.6	Tr.		0.60	1.22	1
			1.62	13.0	10.82	86.8	0.01	0.13	5.0		1

Index Number	Well Depth Date Sampled (feet)	TDS ppm	Na		K		Ca		Mg		Na + K	
			epm	%	epm	%	epm	%	epm	%	epm	%
249	121 -5-68	432					2.93	Ca +	Mg = 44.8		3.11	47.6
269	130 -8-68	894					4.71	Ca +	Mg = 33.8		9.24	66.2
280	125 -3-59	1692					11.88	Ca +	Mg = 48.3		12.70	51.7
286	70 -12-73	1534	23.45	93.5	0.05	0.2	1.05	4.2	0.41	1.6		
287	180 -68	1906					0.50	Ca +	Mg = 1.7		29.23	98.3
311	100 7-4-76	959	13.62	76.8	0.05	0.28	3.29	18.6	0.74	4.2	13.67	77.1
313	110 -68	2090					0.92	Ca +	Mg = 3.0		29.71	97.0
3.18	100	1360					1.35	6.3	1.23	5.7	18.93	87.8
322	150 -74	1544	24.45	96.0	0.23	0.9	0.70	2.8	0.08	0.3	24.68	96.9
327	50 7-6-65	704					0.30	2.5	0.17	1.4	11.64	96.1
329	140 15-4-77	766	13.57	95.4	0.036	0.25	0.45	3.2	0.17	1.2	13.61	95.6
336	82 21-4-78	729	12.18	98.3	0.023	0.19	0.10	0.81	0.082	0.66	12.20	98.5
337	125 -6-70	1010					0.60	Ca +	Mg = 3.7		15.5	96.3
342	64 12-10-65	440					1.05	14.1	3.54	47.6	2.75	37.1
349	98 3-6-68	1026	19.64	98.1			0.36	Ca +	Mg = 1.8			98.1
356	120 -5-74	922	12.53	75.9	0.02	0.12	3.89	23.6	0.082	0.5	12.55	76.0
1-2	27-7-78	419	1.14	13.8	0.13	1.5	4.29	51.8	2.72	32.8	1.27	15.3
2-10	150 28-7-78	1355	3.18	13.0	0.10	0.4	6.09	24.9	15.06	61.7	3.28	13.4
2-11	POUND 28-7-78	453	1.52	18.2	0.66	7.9	3.04	36.4	3.13	37.4	2.18	26.1
3-1A	SPRING 29-7-78	967	12.22	69.6	0.05	0.3	2.4	13.6	2.88	16.4	12.27	69.9

Ca/Mg	Cl		SO_4		$HC0_3$ + CO_3		NO_3		Fe	F	Facies
ratio	epm	%	epm	%	epm	%	epm	%	ppm	ppm	Type
	0.11	1.7	2.67	40.8	3.74	57.2	0.00	0.09	13.95	0.20	4
	0.11	0.8	4.77	34.2	8.93	64.0				2.70	1
	0.09	0.4	13.26	53.9	11.21	45.6	0.01	0.06	0.20	0.20	4
2.56	0.028		11.45		13.34		0.01		3.60	0.31	3
	0.06	0.2	15.37	51.7	14.26	48.0			0.18	0.78	3
4.45	0.028	0.2	5.46	34.7	10.26	65.1	Tr.		0.90	0.15	1
	0.11	0.36	16.45	53.7	14.05	45.9			0.38	0.55	3
1.10	0.17	0.79	9.89	45.9	11.51	53.4			1.60		3
8.50	0.25	1.0	12.03	48.9	12.15	49.4	0.00		0.50	0.96	3
1.77	0.23	1.9	1.98	16.4	9.83	81.2			0.10	1.30	1
2.65	0.09	0.7	2.12	15.8	11.12	83.0	0.02	0.15	0.30	1.00	1
1.22	0.056	0.4	2.79	21.2	10.29	78.1	Tr.		Tr.	0.63	1
	0.11	0.7	4.31	26.8	11.68	72.6			0.06		1
0.30	0.45	6.1	1.12	15.1	5.82	78.3			2.40	0.80	2
	0.056	0.33	5.04	30.0	11.67	69.4			0.55	0.93	1
	0.03	0.2	3.75	23.3	12.29	76.2	Tr.		Tr.	0.88	1
1.58	0.11	1.4	0.67	8.1	7.44	90.3	0.02	0.3	0.10		2
0.40	0.34	1.4	13.33	55.5	10.24	42.7	0.09	0.4	0.30	0.20	4
0.97	0.11	1.5	3.12	41.1	4.28	56.3	0.09	1.2	0.70	0.40	4
0.83	0.11	0.7	5.21	31.5	11.19	67.7	0.02	0.1	0.70	0.40	1

Index Number	Well Depth Date Sampled (feet)	TDS ppm	Na		K		Ca		Mg		Na + K	
			epm	%	epm	%	epm	%	epm	%	epm	%
3-18	CREEK 29-7-78	494	5.48	60.7	0.18	2.0	1.15	12.7	2.22	24.6	5.66	62.7
3-7	CREEK 29-7-78	476	5.57	60.7	0.18	2.0	1.20	13.1	2.22	24.2	5.75	62.7
4-1	266 1-8-78	1357	10.79	45.2	0.20	0.9	5.74	24.0	7.16	30.0	10.99	46.1
4-3	SPRING 1-8-78	852	14.57	84.1			1.2	6.9	1.55	8.9	14.57	84.1
5-1A	250 2-8-78	586	4.61	35.4	0.10	0.8	3.29	25.3	5.02	38.6	4.71	36.2
5-1B	SPRING 2-8-78	490	5.18	42.4	0.10	0.0	3.39	27.8	3.54	29.0	5.28	43.2
5-2	SPRING 2-8-78	454	2.83	23.8	0.10	0.9	3.69	31.1	5.27	44.3	2.93	24.7
5-3A	160 2-8-78	644	11.79	97.7	0.20	1.7	0.07	0.6			11.90	99.4
5-38	POND 2-8-78	2446	28.27	70.8	0.87	2.2	0.52	1.3	10.29	25.7	29.14	73.0
5-5	58 2-8-78	769	9.83	69.3	0.15	1.1	2.15	15.1	2.06	14.5	9.98	70.4
5-6	SPRING 2-8-78	876	11.05	71.1	0.10	0.7	1.85	11.9	2.55	16.4	11.15	71.8
6-1	70 3-8-78	831	2.78	17.6	0.61	3.9	5.74	36.3	6.67	42.2	33.9	21.5
6-2	SPRING 3-8-78	642	4.48	34.9	0.06	0.5	4.19	32.6	4.12	32.0	4.53	35.4
6-3	SLOUGH 3-8-78	830	6.66	42.2	1.46	9.2	1.90	12.0	5.76	36.5	8.12	51.4
6-4	15 3-8-78	1030	13.27	74.1	0.05	0.3	2.20	12.3	2.39	13.3	13.32	74.4
6-5	132 3-8-78	1177	17.79	86.2	0.03	0.15	1.39	6.7	1.42	6.9	17.82	86.35
6-6	220 3-8-78	716	12.79	99.4		0.0	0.07	0.5			12.86	99.4
6-7	SPRING 3-8-78	1080	15.92	86.7	0.05	0.3	1.03	5.6	1.36	7.40	15.97	87.0
6-8	SPRING 3-8-78	1241	15.35	73.0	0.08	0.4	2.54	12.1	3.05	14.5	15.43	73.4

Ca/Mg	Cl		SO_4		$HC0_3$ + CO_3		NO_3		Fe	F	Facies
ratio	epm	%	epm%		epm	%	epm	%	ppm	ppm	Type
0.52	0.17	1.9	1.25	14.2	7.33	83.4	0.04	0.4	0.20	0.40	1
0.54	0.11	1.3	1.25	14.4	7.27	83.7	0.05	0.6	0.30	0.40	1
0.80	0.23	1.0	11.76	52.2	10.52	46.7	0.01	0.0	0.40		4
0.78	Tr.		4.37	27.1	11.72	72.6	0.06		0.60	0.20	2
0.66	0.11	0.9	2.69	21.1	9.93	77.9	0.01	0.08	1.40		2
0.96	0.11	0.9	1.75	14.5	10.16	84.5	0.00	0.0	0.10	0.90	2
0.70	0.11	1.0	1.71	14.9	9.64	84.0	0.02	0.2	0.10	0.20	2
	0.23	1.9	0.07	0.6	11.52	97.5	00.0	0.0	0.30	0.10	1
	0.96	2.4	22.74	56.4	16.62	41.2	0.01	0.00		3.20	3
1.04	0.17	1.2	2.85	21.0	10.52	77.6	0.01	0.1	0.70	0.20	1
0.73	0.11	0.8	5.43	36.2	9.44	63.0	0.01	0.0	0.10	0.30	1
0.86	0.68	4.4	3.62	23.8	10.67	70.0	0.27	1.7	0.40	0.90	2
1.02	0.06	0.5	3.29	29.0	7.8	68.7	0.21	1.8	0.60	0.10	2
0.33	0.28	1.9	2.62	17.7	11.81	79.9	0.07	0.5	0.50	0.40	2
0.92	0.11	0.6	6.20	35.3	11.24	63.9	0.03	0.2	0.10	0.10	1
0.98	0.11	0.56	8.06	40.8	11.56	58.6	0.01	0.05	0.10	0.40	3
2.44	0.11	0.90	2.27	18.3	10.00	80.7	0.02	0.10	0.10	1.10	1
0.76	0.06	0.3	5.85	33.5	11.56	66.1	0.02	0.10	0.30	0.60	1
0.83	0.06	0.3	9.47	45.7	11.19	54.0	0.00	0.0	1.20	0.20	3

Index Number	Well Depth Date Sampled (feet)	TDS ppm	Na		K		Ca		Mg		Na + K	
			epm	%	epm	%	epm	%	epm	%	epm	%
6-9	140 3-8-78	740	13.44	98.8	0.02	0.2	0.12	0.9	0.02	0.1	13.46	99.0
7-1	SPRING 4-8-78	768	10.92	77.6	0.05	0.35	1.55	11.0	1.55	11.0	10.97	78.0
7-3	SPRING 4-8-78	862	14.27	95.2	0.00	0.0	0.50	3.4	0.21	1.4	14.27	95.2
7-5	SPRING 4-8-78	402	2.17	29.9	0.07	1.0	3.27	45.1	1.74	24.0	2.24	30.9
7-6	78 4-8-78	446	2.87	36.2	0.10	1.2	3.39	42.8	1.56	19.7	2.97	37.4
7-7	140 4-8-78	520	0.98	8.7	0.05	0.4	5.59	49.6	3.56	31.6	1.03	9.1
7-8	205 4-8-78	876	13.88	83.7	0.01	0.06	1.22	7.4	0.76	4.6	13.89	83.8
8-1	70 7-8-78	1236	14.96	68.1	0.04	0.18	3.32	15.1	3.65	16.6	15.00	68.3
8-4	120 7-8-78	839	5.65	39.3	0.08	0.60	5.34	37.2	3.29	22.9	5.73	39.9
8-5	SPRING 7-8-78	566	2.52	23.2	0.08	0.7	4.88	45.0	3.29	30.3	2.60	23.9
8-6	125 7-8-78	1328	18.05	77.6	0.01	0.04	2.65	11.4	2.55	11.0	18.06	78.0
8-7	200 7-8-78	654	5.35	47.3	0.13	1.1	4.69	24.7	3.13	26.9	5.48	48.4
9-1	123 8-8-78	1020	18.09	98.9	0.00	0.0	0.15	0.8	0.06	0.3	18.09	98.9
9-1B	74 8-8-78	770	9.96	83.1	0.03	0.3	0.10	0.8	1.89	15.8	9.99	83.4
9-3	SPRING 8-8-78	1039	14.27	76.0	0.00	0.0	2.20	11.7	2.3	12.3	14.27	76.0
9-4	60 8-8-78	964	2.74	16.7	0.05	0.3	5.69	34.7	7.9	48.2	2.79	17.0
9-6	180 8-8-78	768	14.05	98.0	0.00	0.0	0.20	1.4	0.08	0.6	14.05	98.0
9-10	120 8-8-78	1140	18.18	96.2	0.00	0.0	0.47	2.5	0.25	1.3	18.18	96.2
9-12	63 8-8-78	646	2.35	20.2	0.15	1.3	4.94	42.5	4.20	36.1	2.50	21.5

Ca/Mg	Cl		SO_4		$HC0_3 + CO_3$		NO_3		Fe	F	Facies
ratio	epm	%	epm	%	epm	%	epm	%	ppm	ppm	Type
6.00	0.17	1.3	1.06	8.0	12.07	90.6	0.02	0.2	0.80	2.60	1
1.00	0.11	0.80	3.27	23.6	10.45	75.4	0.03	0.21	0.20	0.70	1
2.38	0.06	0.40	2.96	20.2	11.64	79.4	0.00	0.0	0.40	0.40	1
188	0.17	2.20	1.01	13.0	6.57	84.8	0.00	0.1	0.50	0.30	2
2.17	0.17	2.0	1.09	12.7	7.24	84.4	0.08	1.0	1.10	0.20	2
1.57	0.11	1.0	3.37	30.3	7.64	68.6	0.00	0.0	30.5	0.10	2
1.61	0.17	1.1	3.77	21.5	11.52	75.8	0.13	0.9	0.20	1.70	1
0.91	0.17	0.8	9.54	45.3	11.28	53.5	0.07	0.3	0.10	0.30	3
1.62	0.28	1.8	4.75	31.1	10.24	67.1	0.00	0.0	3.7	0.10	2
1.48	0.17	1.5	1.71	14.6	9.83	83.8	1.3	0.02	0.40	0.20	2
1.04	0.68	2.9	9.93	42.8	12.12	52.2	0.48	2.1	0.40	0.80	3
1.50	0.56	4.9	3.08	27.0	9.38	64.7	0.38	3.4	1.50	0.20	2
2.50	0.11	0.6	4.06	23.4	13.16	75.8	0.04	0.2		0.40	1
0.05	0.17	1.2	3.91	28.8	9.47	69.7	0.04	0.3		0.40	1
0.96	0.06	0.3	5.95	35.4	11.41	65.5	0.00	0.0	0.50	0.20	1
0.72	0.39	2.4	4.48	27.5	10.83	66.7	0.54	3.3		0.20	2
2.50	0.11	0.80	1.77	12.8	11.95	86.2	0.03	0.2		1.60	1
1.88	0.17	0.9	5.60	31.1	12.19	67.7	0.05	0.3		0.50	1
1.18	0.11	1.0	2.83	24.2	8.75	74.8	0.00	0.0		0.10	2

Index Number	Well Depth Date Sampled (feet)	TDS ppm	Na		K		Ca		Mg		Na + K	
			epm	%	epm	%	epm	%	epm	%	epm	%
9-13	100 8-8-78	590	6.96	69.1	0.04	0.4	1.65		1.42	14.1	7.00	69.5
9-14	130 8-8-78	822	14.96	98.5	0.00	0.0	0.19	1.2	0.03	0.20	14.96	98.5
9-15	SPRING 8-8-78	526	1.74	18.6	0.05	0.6	4.59	49.1	2.96	31.7	1.79	19.2
10-1	SPRING 9-8-78	850	12.88	85.2	0.01	0.07	1.55	10.3	0.67	4.4	12.89	85.3
10-2	SPRING 9-8-78	953	15.18	90.0	0.01	0.10	0.77	4.6	0.91	5.4	15.19	90.1
10-3	85 9-8-78	982	14.7	89.3	0.00	0.0	0.54	3.3	1.22	7.4	14.7	89.3
10-4	SPRING 9-8-78	928	9.79	64.7	0.00	0.0	2.79	18.5	2.55	16.9	9.79	64.7
10-5	SPRING 9-8-78	832	12.66	85.5	0.00	0.0	1.45	9.8	0.70	4.7	12.66	85.5
10-6	50 9-8-78	894	9.18	62.1	0.01	0.1	3.04	20.6	2.55	17.3	9.19	62.2
10-7	SPRING 9-8-78	690	7.83	63.3	0.00	0.0	2.64	21.4	1.89	15.3	7.83	63.3
10-8	SPRING 9-8-78	642	3.96	33.1	0.01	0.1	3.64		4.36		3.97	33.2
10-9	180 9-8-78	828	14.62	98.9	0.00	0.0	0.12	0.8	0.03	0.2	14.62	98.9
10-10	107 9-8-78	836	11.92	83.9	0.00	0.0	0.56	4.0	1.73	12.2	11.92	83.9
11-1	170 10-8-78	695	12.01	99.2	0.00	0.0	0.07	0.6	0.02	0.10	12.01	99.2
11-2	SPRING 10-8-78	678	11.53	97.0	0.00	0.0	0.23	2.0	0.12	1.0	11.53	97.0
11-3	SPRING 10-8-78	808	12.66	92.0	0.03	0.2	0.43	3.1	0.63	4.6	12.69	92.2
11-6	170 10-8-78	732	12.44	97.4	0.02	0.2	0.21	1.6	0.10	0.8	12.46	97.6
11-7	SPRING 10-8-78	388	1.85	21.6	0.06	0.7	3.72	43.5	2.92	34.2	1.91	22.3
11-8	105 10-8-78	770	13.61	98.1	0.01	0.1	0.19	1.4	0.06	0.4	13.62	98.2

Ca/Mg	Cl		SO_4		$HC0_3 + CO_3$		NO_3		Fe	F	Facies
ratio	epm	%	epm	%	epm	%	epm	%	ppm	ppm	Type
1.16	0.11	1.1	2.02	19.5	8.16	78.8	0.06	0.6		0.20	1
6.33	0.11	0.8	2.48	16.9	12.08	82.2	0.03	0.2		0.40	1
1.47	0.11	1.1	1.37	14.0	8.36	84.9	0.00	0.0		0.20	2
2.31	0.11	0.7	3.04	20.2	11.67	77.6	0.21	1.4	1.10	0.50	1
0.85	0.06	0.4	4.62	28.7	11.39	70.8	0.03	0.2		0.30	1
0.44	0.06	0.4	5.10	31.7	10.92	67.9	0.01	0.1		0.40	1
1.02	0.11	0.8	3.39	23.1	11.19	76.1	0.00	0.0	0.00	0.20	1
2.07	0.06	0.4	3.04	21.1	11.24	78.2	0.04	0.3	0.30	0.90	1
1.19	0.11	0.7	3.83	25.4	11.11	73.8	0.00	0.0		0.30	1
1.40	0.06	0.5	2.17	17.6	10.11	82.0	0.00	0.0	0.00	0.20	1
0.84	0.06	0.5	1.64	14.3	9.75	84.9	0.04	0.3		0.10	2
4.00	0.11	0.8	2.96	21.4	10.71	77.6	0.02	0.2		1.60	1
0.33	0.06	0.4	3.96	29.0	9.6	70.4	0.02	0.2		0.20	1
3.50	0.34	2.6	1.06	8.2	11.52	89.0	0.02	0.2		1.20	1
1.97	0.06	0.5	1.60	13.7	10.07	85.8	0.00	0.0		0.50	1
0.68	0.06	0.4	3.33	24.8	10.24		0.02	0.2		0.70	1
2.10	0.06	0.5	2.19	17.8	10.00	81.4	0.04	0.3		0.80	1
1.27	0.06	0.65	0.83	9.0	8.29	89.7	0.06	0.65	0.10	0.20	2
3.17	0.23	1.7	1.85	13.6	11.48	84.5	0.02	0.10		1.10	1

Index Number	Well Depth Date Sampled (feet)	TDS ppm	Na		K		Ca		Mg		Na + K	
			epm	%	epm	%	epm	%	epm	%	epm	%
11-9	SPRING 10-8-78	396	1.69	21.5	0.06	0.8	2.30	29.3	3.79	48.3	1.75	22.3
11-10	SPRING 10-8-78	814	9.96	68.8	0.04	0.3	2.25	15.5	2.22	15.4	10.00	68.9
12-1	SPRING 11-8-78	734	7.87	58.1	0.06	0.5	2.74	20.2	2.88	21.2	7.93	58.6
12-2	SPRING 11-8-78	844	10.40	69.6	0.04	0.3	1.95	13.0	2.55	17.1	10.44	69.9
12-3	255 11-8-78	846	14.75	96.5	0.00	0.0	0.30	2.0	0.24	1.6	14.75	96.5
12-4	100 11-8-78	460	3.61	41.9	0.04	0.5	1.10	12.7	3.87	44.9	3.65	42.4
12-5	SPRING 11-8-78	722	9.26	75.7	0.05	0.4	0.12	1.0	2.8	22.9	9.31	76.1
12-7	180 11-8-78	1008	16.79	98.6	0.00	0.0	0.17	1.0	0.07	0.4	16.79	98.6
12-8	72 11-8-78	296	2.39	48.7	0.02	0.4	0.92	18.8	1.58	32.1	2.41	49.1
13-1	80 15-8-78	430	1.04	12.5	0.07	0.9	3.44	41.7	3.7	44.9	1.11	13.4
13-2	SPRING 15-8-78	370	2.35	34.5	0.06	0.9	2.35	34.4	2.06	30.2	2.41	35.4
13-4	SPRING 15-8-78	356	1.36	18.4	0.05	0.7	3.09	41.9	2.88	39.0	1.41	19.1
13-5	SPRING 15-8-78	660	6.26	50.4	0.03	0.3	2.99	24.1	3.13	25.2	6.29	50.7
14-1	175 17-8-78	902	11.53	70.0	0.00	0.0	3.44	20.9	1.49	9.1	11.53	70.0
14-2	90 17-8-78	750	12.61	89.4	0.00	0.0	1.10	7.8	0.40	2.8	12.61	89.4
14-3	37 17-8-78	358	2.78	31.8	0.02	0.2	3.93	45.0	2.00	22.9	2.80	32.0
14-4	SPRING 17-8-78	578	6.92	61.4	0.05	0.5	2.94	26.1	1.35	12.0	6.97	61.9
14-5	98 17-8-79	616	8.39	67.4	0.04	0.3	2.61	21.0	1.40	11.3	8.43	67.7
14-6	80 17-8-78	664	5.92	46.5	0.06	0.47	4.65	36.5	2.10	16.5	5.98	46.97

Ca/Mg	Cl		SO_4		HCO_3 + CO_3		NO_3		Fe	F	Facies
ratio	epm	%	epm%		epm	%	epm	%	ppm	ppm	Type
0.61	0.17	2.1	0.92	11.4	6.92	86.2	0.02	0.20		0.10	2
1.01	0.11	0.8	2.96	21.4	10.72	77.5	0.04	0.3		0.20	1
0.95	0.06	0.4	2.67	20.4	10.31	79.1	0.01	0.1		0.10	2
0.77	0.17	1.1	3.44	23.2	11.08	74.9	0.11	0.8		0.10	1
1.25	0.06	0.4	2.81	19.1	11.80	80.2	0.05	0.3		0.20	1
0.28	0.11	1.3	1.31	14.6	7.56	84.1	0.00	0.1		0.10	2
0.04	0.11	0.9	2.56	20.1	10.00	78.5	0.06	0.5		0.10	1
2.43	0.06	0.3	4.06	24.9	12.16	74.6	0.03	0.2		0.40	1
0.58	0.17	3.2	0.51	9.5	4.63	86.3	0.05	1.0		0.30	2
0.94	0.28	3.3	0.67	8.0	7.11	83.8	0.41	4.9	0.70	0.10	2
1.21	0.17	2.3	0.51	7.0	6.67	90.6	0.00	0.1	0.30	0.10	2
1.14	0.11	1.5	0.51	6.7	6.97	91.4	0.03	0.4	0.60	0.10	2
1.08	0.11	0.9	3.41	27.0	9.11	72.1	0.01	0.1	0.30	0.10	2
2.39	0.34	2.2	3.33	21.3	11.92	76.3	0.04	0.2	0.20	0.60	1
2.75	0.11	0.8	1.96	13.8	12.03	85.1	0.04	0.3	0.10	0.40	1
1.97	0.34	3.7	1.04	11.3	7.83	84.9	0.01	0.1	0.90	0.20	2
2.13	0.06	0.5	1.52	13.6	9.52	85.5	0.04	0.4	2.70	0.30	1
1.86	0.06	0.49	1.79	14.5	10.47	84.9	0.01	0.08	0.40	0.40	1
2.21	0.11	0.90	3.29	26.9	8.80	71.8	0.05	0.41	5.70	0.20	2

Index Number	Well Depth Date Sampled (feet)	TDS ppm	Na		K		Ca		Mg		Na + K	
			epm	%	epm	%	epm	%	epm	%	epm	%
14-8	17-8-78	910	16.09	98.7	0.00	0.0	0.18	1.1	0.02	0.2	16.09	98.7
14-9	SPRING 17-8-78	734	12.61	97.4	0.00	0.0	0.26	2.0	0.07	0.6	12.61	97.4
14-10	125 17-8-78	1412	22.75	96.8	0.00	0.0	0.57	2.4	0.17	0.7	22.75	96.8
14-11	SPRING 17-8-78	972	14.14	79.7	0.00	0.0	2.55	14.4	1.05	5.9	14.14	79.7
14-12	80 17-8-78	1350	22.23	96.8	0.03	0.13	0.471	2.1	0.17	0.74	22.26	96.9
15-1	SPRING 18-8-78	340	1.85	26.9	0.07	1.1	3.04	44.4	1.89	27.6	1.92	28.0
15-2	200 18-8-78	1018	18.40	98.4	0.02	0.1	0.23	1.3	0.07	0.4	18.42	98.5
15-3	300 18-8-78	764	14.05	98.7	0.01	0.1	0.14	1.0	0.05	0.2	14.06	98.8
15-4	200 18-8-78	798	14.05	98.8	0.00	0.0	0.14	10.0	0.03	0.2	14.05	98.8
15-5	200 18-8-78	1268	19.92	95.2	0.04	0.2	0.60	2.9	0.36	1.7	19.96	95.4
15-6	198 18-8-78	1224	19.27	92.9	0.19	0.9	0.93	4.5	0.36	1.7	19.46	93.8
15-7	242 18-8-78	754	12.74	97.4	0.00	0.0	0.24	1.8	0.10	0.8	12.74	97.4
15-8	60 18-8-78	1479	24.05	92.2	0.04	0.2	1.35	5.2	0.64	2.5	24.09	92.4
15-10	90 18-8-78	914	13.92	92.5	0.00	0.0	0.79	5.3	0.34	2.2	13.92	92.5
15-11	SPRING 18-8-78	348	0.60	8.4	0.25	3.5	4.49	63.0	1.78	25.0	0.85	11.9
15-12	85 18-8-78	1212	19.14	96.6	0.00	0.0	0.48	2.4	0.18	0.9	19.14	96.6
15-13	80 18-8-78	1144	18.40	98.4	0.00	0.0	0.22	1.2	0.07	0.4	18.44	98.4
16.2	SPRING 19-8-78	624	4.31	34.2	0.04	0.3	4.60	36.5	3.65	29.0	4.35	34.5
16-3	100 19-8-78	1038	13.01	76.8	0.00	0.0	2.69	15.9	1.23	7.2	13.01	76.8

Ca/Mg	Cl		SO_4		HCO_3 + CO_3		NO_3		Fe	F	Facies
ratio	epm	%	epm%		epm	%	epm	%	ppm	ppm	Type
9.00	0.11	0.70	5.04	32.5	10.31	66.5	0.03	0.2	0.10	0.80	1
3.95	0.11	0.90	1.92	15.2	10.56	83.8	0.02	0.2	0.10	0.50	1
3.34	0.06	0.30	6.58	30.4	14.95	69.1	0.04	0.2	0.90	0.40	1
2.43	0.06	0.35	4.73	27.8	12.15	71.5	0.05	0.3	0.30	0.20	1
2.77	0.06	0.26	7.35	32.0	14.69	64.0	0.05	0.22	1.80	0.30	1
1.70	0.23	3.2	0.51	7.2	6.28	89.0	0.04	0.6	0.00	0.20	2
3.19	0.11	0.6	3.25	18.3	14.28	80.5	0.03	0.2	0.10	1.30	1
3.16	0.23	1.7	2.62	19.7	10.45	78.4	0.02	0.2	0.00	1.10	1
6.75	0.17	1.2	3.29	23.8	10.31	74.8	0.02	0.2	0.30		1
1.71	0.11	0.6	8.06	42.2	10.88	57.0	0.05	0.3	0.10	0.40	3
2.61	0.17	0.9	6.00	30.7	13.31	68.2	0.04	0.2	0.30	0.50	1
2.48	0.11	0.8	5.29	36.9	8.88	62.0	0.05	0.4	0.10	0.90	1
3.09	0.11	0.5	9.60	40.9	13.72	58.4	0.06	0.3	1.80	0.30	3
2.41	0.11	0.8	3.77	27.2	9.92	71.7	0.04	0.3	0.30	0.70	1
2.52	0.45	5.9	0.62	8.2	6.2	81.9	0.30	4.0	0.10	0.10	2
2.62	0.06	0.3	6.12	33.4	12.11	66.1	0.03	0.2	0.10	0.40	1
2.55	0.17	0.9	6.00	32.6	12.19	66.3	0.03	0.2	0.00	0.40	1
1.26	0.11	0.9	2.83	23.0	9.36	76.0	0.01	0.08	0.00	0.10	2
2.20	0.06	0.3	6.02	36.3	10.44	63.0	0.06	0.4	1.50	0.10	1

Index Number	Well Depth Date Sampled (feet)	TDS ppm	Na		K		Ca		Mg		Na + K	
			epm	%	epm	%	epm	%	epm	%	epm	%
16-4	125 19-8-78	1578	25.14	97.8	0.01	0.0	0.45	1.7	0.11	0.4	25.14	97.8
16-6	200 19-8-78	1298	22.36	97.9	0.02	0.1	0.36	1.6	0.10	0.4	22.38	98.0
P-1	CREEK 1-11-77	700	9.79	74.7	0.15	1.1	1.11	8.5	2.06	15.7	9.94	75.8

Ca/Mg	Cl		SO_4		HCO_3 + CO_3		NO_3		Fe	F	Facies
ratio	epm	%	epm	%	epm	%	epm	%	ppm	ppm	Type
3.92	0.11	0.5	10.58	43.5	13.56	55.9	0.05	0.2	0.30	0.20	2
3.34	0.17	0.8	7.75	35.9	13.64	63.1	0.05	0.2	0.40	0.40	1
0.54	0.11	0.9	3.66	27.7	9.45	71.5	0.00	0.0		0.40	1

APPENDIX C: Deep Well Data

Notes to Appendix C

1. Column 1: The letter in the index indicates the following type of well: S = structure test hole, C = coal test hole and H = gas or oil test hole.
2. Column 3: Datum elevation refers to the elevation from which the geophysical well logs are measured as zero depth. In most cases this is a surveyed land or ground elevation. The letters G.L. beside the number indicate ground level, while the letter K.B. indicate a Kelly Bushing elevation.
3. Columns 6 to 8: The abbreviation L. Ardley 'B' stands for Lower Ardley 'B' coal zone.
4. Columns 9 and 10: These columns refer to the amount of sandstone (cumulative) in the strata above the Lower Ardley 'B' coal zone.

Elevation of L. Ardley 'B' (feet)	Thickness of L. Ardley 'B' (feet)	Thickness of Sandstone (feet)	Percent Sandstone	Depth to Bedrock (feet)
2612	16	270	79	
2593	17	100	48	
2583	18	136	37	
2584	20	200	61	107
2529	17	213	45	
2601	18	128	67	48
2609	16	160	44	
2599	17	262	66	20
2507	19	262	54	
2508	18	160	29	
2508	17	200	17	
2468	21	130	21	
2484	17	150	26	
2487	17	224	41	
2453	17	324	50	
2462	21	335	56	
2443	21	228	37	83
2448	19	260	39	89
2427	21	320	45	
2466	20	285	42	36
2545	17	185	43	
2515	17	170	47	60

Index Number	Location	Datum Elevation (feet)	Depth Logged (feet)	Company Date	Depth to top of L. Ardley 'B' (feet)
S-1	13-36-34-24W4	3003	855	July 19, 1953	391
S-2	15-34-34-24W4	2850	650	July 14, 1953	257
S-3	3-3-35-24W4	3000	755	July 17, 1953	415
S-4	2-4-35-24W4	2960	758	June 9, 1953	376
S-5	13-6-35-24W4	3055	905	Gulf Oil Nov. 3, 1952	526
S-6	9-10-35-24W4	2842	770	June 9, 1953	241
S-7	9-13-35-24W4	3020	862	July 13, 1953	411
S-8	1-14-35-24W4	3045	843	June 8, 1953	446
S-9	13-2-35-25W4	3042	919	Gulf Oil Nov. 8, 1952	535
S-10	13-12-35-25W4	3109	960	Gulf Oil Oct. 31, 1952	601
S-11	16-12-35-25W4	3104	906	Gulf Oil Nov. 2, 1952	596
S-12	4-23-35-25W4	3152	1059	Gulf Oil Oct. 25, 1952	684
S-13	4-24-35-25W4	3106	1006	Gulf Oil Oct. 22, 1952	622
S-14	16-24-35-25W4	3057	967	Gulf Oil Oct. 29, 1952	570
S-15	4-26-35-25W4	3152	804	Chevron Aug. 27, 1951	699
S-16	4-27-35-25W4	3116	774	Chevron Sept. 14, 1951	654
S-17	4-28-35-25W4	3109	803	Chevron Aug. 23, 1951	666
S-18	13-32-35-25W4	3167	909	Chevron Aug. 21, 1951	719
S-19	4-33-35-25W4	3183	814	Chevron Oct. 30, 1951	756
S-20	4-34-35-25W4	3191	800	Chevron Oct. 17, 1953	725
S-21	1-4-36-24W4	3025	627	Chevron Aug. 21, 1951	480
S-22	13-32-35-24W4	2928	569	Chevron Aug. 17, 1951	413

Index Number	Location	Datum Elevation (feet)	Depth Logged (feet)	Company Date	Depth to top of L. Ardley 'B' (feet)
S-23	13-7-36-24W4	2970	556	Chevron Nov. 13, 1951	484
S-24	13-11-36-24W4	3050	553	Chevron Dec. 2, 1951	479
S-25	4-16-36-24W4	3057	600	Chevron Dec. 2, 1951	528
S-26	12-24-36-24W4	2710	416	Royalite Oil Aug. 23, 1952	
S-27	13-24-36-24W4	3052	526	Royalite Oil June 19, 1952	503
S-28	4-26-36-24W4	3053	606	Chevron Nov. 7, 1951	489
S-29	4-27-36-24W4	3122	636	Royalite Oil Sept. 11, 1952	591
S-30	1-30-36-24W4	3000	557	Royalite Oil Sept. 16, 1952	503
S-31	13-35-36-24W4	2981	490	Royalite Oil July 3, 1952	427
S-32	4-1-36-25W4	3022	701	Chevron Aug. 16, 1951	557
S-33	4-2-36-25W4	3088	711	Chevron Sept. 21, 1951	619
S-34	4-3-36-25W4	3136	850	Chevron Aug. 14, 1951	709
S-35	4-4-36-25W4	3211	851	Chevron Sept. 14, 1951	775
S-36	4-6-36-25W4	3044	676	Chevron Oct. 28, 1951	609
S-37	4-7-36-25W4	3090	755	Chevron Sept. 18, 1951	657
S-38	13-7-36-25W4	3143	804	Chevron Sept. 18, 1953	729
S-39	4-8-36-25W4	3148	786	Chevron Sept. 25, 1951	731
S-40	16-8-36-25W4	3239	901	Chevron Aug. 29, 1951	798
S-41	4-11-36-25W4	3068	1018	Chevron Nov. 28, 1951	599

Elevation of L. Ardley 'B' (feet)	Thickness of L. Ardley 'B' (feet)	Thickness of Sandstone (feet)	Percent Sandstone	Depth to Bedrock (feet)
2486	15	120	28	
2571	15	215	50	
2529	15	182	38	
2549	14	226	50	42
2564	14	162	37	
2531	14	248	46	
2497	14	175	39	55
2554	14	150	40	50
2465	16	208	41	
2469	17	220	39	
2427	23	246	37	
2436	20	406	56	
2435	21	270	48	86
2433	19	328	54	
2414	19	296	44	70
2417	19	330	49	77
2441	16	290	39	
2469	17	100	18	

Index Number	Location	Datum Elevation (feet)	Depth Logged (feet)	Company Date	Depth to top of L. Ardley 'B' (feet)
S-42	4-14-36-25W4	3012	607	Chevron Nov. 8, 1951	560
S-43	13-15-36-25W4	3113	1042	Chevron Nov. 24, 1951	661
S-44	4-17-36-25W4	3220	849	Chevron Sept. 21, 1951	797
S-45	4-18-36-25W4	3148	850	Chevron Sept. 6, 1951	790
S-46	4-18-36-25W4	3148	1253	Chevron Nov. 20, 1951	791
S-47	13-19-36-25W4	3171	1248	Chevron Oct. 16, 1951	774
S-48	13-20-36-25W4	3193	852	Chevron Sept. 11, 1951	774
S-49	13-22-36-25W4	3038	682	Chevron Nov. 1, 1951	559
S-50	13-23-36-25W4	2925	550	Chevron Nov. 4, 1951	443
S-51	1-25-36-25W4	3008	548	Chevron Nov. 5, 1951	517
S-52	9-26-36-25W4	2990	624	Chevron Dec. 11, 1951	505
S-53	1-26-36-25W4	2969	540	Chevron Dec. 20, 1951	487
S-54	3-26-36-25W4	2970	575	Royalite Oil Sept. 16, 1952	491
S-55	5-28-36-25W4	3112	740	Chevron Nov. 5, 1951	668
S-56	13-32-36-25W4	3123	1090	Chevron Nov. 23, 1951	718
S-57	1-33-36-25W4	3035	602	Chevron Dec. 21, 1951	564
S-58	4-35-36-25W4	2945	553	Chevron Dec. 19, 1951	471
S-59	4-12-36-26W4	3024	744	Chevron Nov. 2, 1951	609
S-60	1-14-36-26W4	3049	801	Chevron 1951	636

Elevation of L. Ardley 'B' (feet)	Thickness of L. Ardley 'B' (feet)	Thickness of Sandstone (feet)	Percent Sandstone	Depth to Bedrock (feet)
2452	15	102	20	60
2452	18	182	30	
2423	17	330	44	
2358	26	282	38	70
2357	25	290	39	66
2397	17	182	25	70
2419	18	162	22	
2479	18	124	24	
2482	19	128	33	137
2491	16	116	25	
2485	16	146	32	80
2482	15	114	26	
2479	15	138	31	52
2444	16	170	28	96
2405	20	234	35	
2471	17	212	41	85
2474	15	164	39	138
2415	20	256	46	
2413	20			

Index Number	Location	Datum Elevation (feet)	Depth Logged (feet)	Company Date	Depth to top of L. Ardley 'B' (feet)
S-61	1-26-36-26W4	3136	870	Chevron Sept. 11, 1951	735
S-62	13-27-36-26W4	3201	1320	Gulf Oct. 21, 1954	852
S-63	4-6-37-24W4	3187	801	Royalite Oil Sept. 16, 1952	689
S-64	4-6-37-24W4	3187	739	Chevron Nov. 12, 1951	690
S-65	13-7-37-24W4	3020	564	Chevron Oct. 18, 1953	498
S-66	4-17-37-24W4	2960	554	Royalite Oil June 7, 1952	419
S-67	4-18-37-24W4	2973	634	Chevron Jan. 3, 1952	468
S-68	13-1-37-25W4	3144	700	Chevron Oct. 11, 1953	658
S-69	13-2-37-25W4	3115	689	Chevron Sept. 16, 1953	642
S-70	1-3-37-25W4	3027	630	Chevron Nov. 10, 1951	571
S-71	13-4-37-25W4	3150	743	Chevron Oct. 11, 1953	696
S-72	2-5-37-25W4	3111	745	Chevron Dec. 7, 1951	649
S-73	16-5-37-25W4	3169	808	Chevron Dec. 22, 1951	711
S-74	4-6-37-25W4	3168	847	Chevron Nov. 29, 1951	786
S-75	1-10-37-25W4	3150	731	Chevron Dec. 12, 1951	679
S-76	5-10-37-25W4	3060	700	Chevron Sept. 11, 1953	592
S-77	13-11-37-25W4	3134	703	Chevron Sept. 15, 1953	653
S-78	13-12-37-25W4	3032	660	Chevron Dec. 1, 1951	573
S-79	1-14-37-25W4	3015	575	Royalite Oil June 9, 1952	522

Elevation of L. Ardley 'B' (feet)	Thickness of L. Ardley 'B' (feet)	Thickness of Sandstone (feet)	Percent Sandstone	Depth to Bedrock (feet)
2401	18	268	39	
2349	20	360	45	
2498	14	286	45	
2497	17	245	38	
2522	13	130	29	150
2541	14	146	40	108
2505	14	140	34	98
2486	15	214	35	68
2473	16	264	45	
2456	17	240	46	57
2454	14	248	38	36
2462	15	168	28	63
2458	15	236	36	52
2382	17	170	23	66
2471	17	290	46	
2468	15	186	34	132
2481	16	196	33	130
2459	15	192	37	114
2493	14	198	42	126

Index Number	Location	Datum Elevation (feet)	Depth Logged (feet)	Company Date	Depth to top of L. Ardley 'B' (feet)
S-80	13-14-37-25W4	3037	612	Chevron Dec. 16, 1951	573
S-81	1-15-37-25W4	3095	732	Chevron Dec. 14, 1951	628
S-82	4-15-37-25W4	3133	1102	Chevron Nov. 27, 1951	640
S-83	4-15-37-25W4	3134	659	Chevron Oct. 6, 1953	640
S-84	4-15-37-25W4	3134	777	Royalite Oil June 10, 1952	639
S-85	7-15-37-25W4	3098	663	Chevron Nov. 30, 1953	600
S-86	16-15-37-25W4	3049	623	Chevron Sept. 14, 1953	571
S-87	4-16-37-25W4	3122	721	Chevron Sept. 13, 1953	650
S-88	16-17-37-25W4	3194	813	Chevron Dec. 23, 1951	727
S-89	1-19-37-25W4	3250	879	Chevron Oct. 10, 1953	830
S-90	16-19-37-25W4	3190	827	Chevron Dec. 9, 1951	767
S-91	13-21-37-25W4	3171	732	Royalite Oil May 28, 1952	701
S-92	4-22-37-25W4	3099	743	Chevron Sept. 8, 1953	631
S-93	4-26-37-25W4	2985	547	Royalite Oil May 27, 1952	491
S-94	4-28-37-25W4	3146	916	Chevron Sept 11, 1953	695
S-95	4-29-37-25W4	3168	810	Chevron Sept. 13, 1953	730
S-96	4-30-37-25W4	3385	1010	Royalite Oil June 3, 1952	955
S-97	13-33-37-25W4	2876	492	Royalite Oil May 22, 1952	469
S-98	4-2-37-26W4	3116	831	Chevron Sept. 7, 1951	786

Elevation of L. Ardley 'B' (feet)	Thickness of L. Ardley 'B' (feet)	Thickness of Sandstone (feet)	Percent Sandstone	Depth to Bedrock (feet)
2464	15	180	34	115
2467	15	206	36	137
2493	14	176	30	
2494	14	174	30	
2495	15	176	30	
2498	16	230	42	104
2478	15	182	35	117
2472	13	284	47	112
2467	15	248	37	85
2420	13	264	34	81
2423	15	240	34	111
2470	15	270	42	120
2468	15	170	29	166
2494	15	138	31	156
2451	14	312	48	132
2438	14	232	34	110
2430	15	286	32	
2407	15	178	43	
2330	22	284	39	

Index Number	Location	Datum Elevation (feet)	Depth Logged (feet)	Company Date	Depth to top of L. Ardley 'B' (feet)
S-99	13-12-37-26W4	3235	924	Chevron Dec. 13, 1951	883
S-100	4-14-37-26W4	3178	1048	Chevron Dec. 1, 1951	836
S-101	13-23-37-26W4	3392	1092	Chevron Dec. 18, 1951	1055
S-102	13-24-37-26W4	3228	973	Chevron Dec. 5, 1951	906
S-103	13-24-37-26W4	3224	936	Chevron Sept. 9, 1953	857
S-104	1-1-38-26W4	2995	740	Royalite Oil May 22, 1952	630
C9-78	13-14-35-24W4	2875	790	A.R.C. Aug. 8, 1978	282
C4-74	12-22-35-25W4	3075 (G.L.) 3079 (K.B.)	693	A.R.C. June 12, 1974	628
C11-74	2-28-36-26W4	3145 (G.L.) 3149 (K.B.)	898	A.R.C. June 19, 1974	779
C12-74	15-22-36-25W4	3030 (G.L.) 3034 (K.B.)	698	A.R.C. June 21, 1974	558
C13-74	16-16-36-24W4	3123 (G.L.) 3127 (K.B.)	793	A.R.C. June 18, 1974	565
H-1	14-2-35-24W4	2858 (G.L.) 2870 (K.B.)	7490	Banff Oil 1954	
H-2	10-8-35-24W4	3031 (G.L.) 3042 (K.B.)	5700	Kerr-McGee 1975	
H-3	10-9-35-24W4	3077 (G.L.) 3089 (K.B.)	5814	Kerr-McGee 1976	
H-4	7-10-35-24W4	2911 (G.L.) 2925 (K.B.)	4916	Camac Expl.	
H-5	6-19-35-24W4	3024 (G.L.) 3047 (K.B.)	7803	Phillips Pet. 1955	
H-6	14-21-35-24W4	2890 (G.L.) 2902 (K.B.)	7512	Husky Oil 1955	347
H-7	6-1-35-25W4	3072 (G.L.) 3085 (K.B.)	8006	B. A. Oil 1956	565
H-10	10-14-35-25W4	3177 (G.L.) 3189 (K.B.)	7065	Zapata Pet. 1962	

Elevation of L. Ardley 'B' (feet)	Thickness of L. Ardley 'B' (feet)	Thickness of Sandstone (feet)	Percent Sandstone	Depth to Bedrock (feet)
2352	15	252	30	
2342	20	266	34	108
2337	16	370	37	
2322	14	228	27	84
2367	14	236	29	73
2365	15	168	29	56
2593	16	100	43	50
2451	20	236	41	25
2370	19	456	63	35
2476	19	170	34	45
2562	14	262	51	25
2555	17	110	39	115
2520	17			

Index Number	Location	Datum Elevation (feet)	Depth Logged (feet)	Company Date	Depth to top of L. Ardley 'B' (feet)
H-11	13-14-35-24W4	3209 (K.B.)	6295	Husky Oil 1955	724
H-12	6-17-35-25W4	3033 (G.L.) 3044 (K.B.)	5813	Amoco Oil 1970	610
H-13	6-21-35-25W4	3098 (G.L.) 3112 (K.B.)	3493	Czar Resources 1977	642
H-14	16-22-35-25W4	3150 (G.L.) 3162 (K.B.)	7850	Peyto Oil 1972	
H-15	6-23-35-24W4	3160 (G.L.) 3173 (K.B.)	7178	Republic Resources 1974	
H-16	4-27-35-25W4	3163 (K.B.)	7998	Federated Pet. 1953	698
H-17	3-30-35-25W4	3043 (G.L.) 3057 (K.B.)	8002	Amurex Oil 1953	609
H-18	6-33-35-25W4	3188 (G.L.) 3203 (K.B.)	5957	Can. Pacific Oil 1964	769
H-19	6-34-35-25W4	3089 (G.L.) 3101 (K.B.)	3247	Phillips Pet. 1952	624
H-20	1-35-35-25W4	3050 (G.L.) 3063 (K.B.)	7067	Seafort Pet. 1966	
H-23	15-2-36-24W4	3068 (G.L.) 3081 (K.B.)	7608	Phillips Pet. 1955	482
H-24	16-5-36-24W4	3015 (G.L.) 3027 (K.B.)	6834	Skelly Oil 1972	
H-25	4-22-36-24W4	3133 (G.L.) 3146 (K.B.)	5867	Great Plains Dev. 1961	
H-27	6-32-36-24W4	3088 (G.L.) 3100 (K.B.)	5590	Seafort Pet. 1966	
H-28	11-5-36-25W4	3218 (G.L.) 3231 (K.B.)	5998	Gibraltar Oil 1972	800
H-29	6-12-36-25W4	2966 (G.L.) 2979 (K.B.)	7120	Skelly Oil 1972	
H-30	6-17-36-25W4	3253 (G.L.) 3265 (K.B.)	6105	Resman Holdings 1975	831
H-31	6-18-36-25W4	3200 (G.L.) 3212 (K.B.)	5366	Resman Holdings 1975	780
H-32	6-20-36-25W4	3223 (G.L.) 3236 (K.B.)	5964	Resman Holdings 1975	805

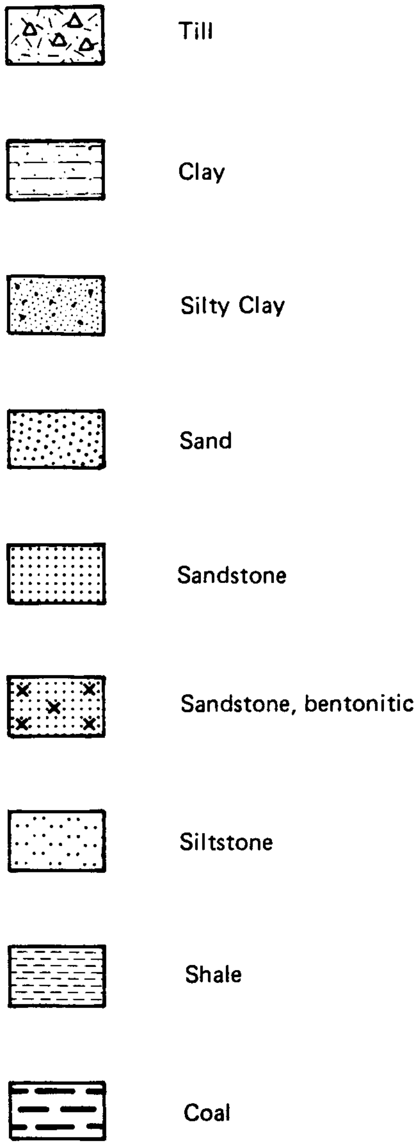
Elevation of L. Ardley 'B' (feet)	Thickness of L. Ardley 'B' (feet)	Thickness of Sandstone (feet)	Percent Sandstone	Depth to Bedrock (feet)
2485	20			
2434				
2470	19			
2465	21			
2448	20			
2434	23			
2477	16			
2599	15	200	48	
2431	19			
2434	18			
2432	19			
2431	17			

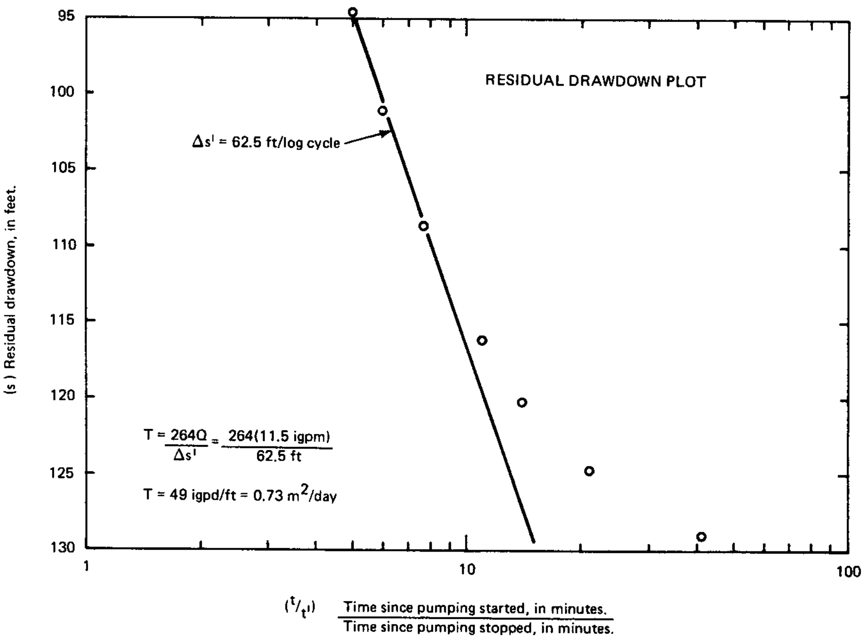
Index Number	Location	Datum Elevation (feet)	Depth Logged (feet)	Company Date	Depth to top of L. Ardley 'B' (feet)
H-33	6-26-36-25W4	3039 (G.L.) 3050 (K.B.)	7075	Imperial Oil 1959	560
H-34	11-32-36-25W4	3092 (G.L.) 3105 (K.B.)	7137	Walnoco Oil 1973	
H-35	7-11-36-26W4	3066 (G.L.) 3080 (K.B.)	5885	Amoco Petroleum 1972	665
H-36	6-12-36-26W4	3030 (G.L.) 3044 (K.B.)	5870	Amoco Petroleum 1972	
H-37	7-13-36-26W4	3084 (G.L.) 3097 (K.B.)	5919	Resman Holdings 1975	678
H-38	6-14-36-26W4	3115 (G.L.) 3128 (K.B.)	7710	Diamond Shamrock 1970	
H-39	2-23-36-26W4	3093 (G.L.) 3105 (K.B.)	7522	Shell Oil 1966	
H-40	16-25-36-26W4	3167 (G.L.) 3180 (K.B.)	7162	Sohio Petroleum 1957	782
H-41	7-36-36-26W4	3165 (G.L.) 3177 (K.B.)	7188	Merland Expl. 1974	786
H-45	10-11-37-25W4	3069 (G.L.) 3085 (K.B.)	7017	Uno-Tex. Pet. 1962	
H-46	16-16-37-25W4	3105 (G.L.) 3118 (K.B.)	6871	Central Del Rio Oils - 1960	
H-47	11-17-37-25W4	3194 (G.L.) 3208 (K.B.)	7090	B. A. Oil 1964	751
H-48	11-23-37-25W4	3026 (G.L.) 3040 (K.B.)	6701	Union Texas Natural Gas 1961	
H-49	4-24-37-25W4	3002 (G.L.) 3016 (K.B.)	6647	Uno-Tex. Pet. 1963	
H-52	1-27-37-25W4	2945 (G.L.) 2957 (K.B.)	6671	Union Texas Natural Gas 1961	
H-53	11-14-37-26W4	3214 (G.L.) 3228 (K.B.)	7356	Sun Oil 1969	878
H-54	10-22-37-26W4	3145 (G.L.) 3157 (K.B.)	6153	Amerada Pet. 1964	812

Elevation of L. Ardley 'B' (feet)	Thickness of L. Ardley 'B' (feet)	Thickness of Sandstone (feet)	Percent Sandstone	Depth to Bedrock (feet)
2490	15	150	30	
2415	19			
2419	20			
2398	17			
2391	17			
2457	16			
2350	22			
2345	20			

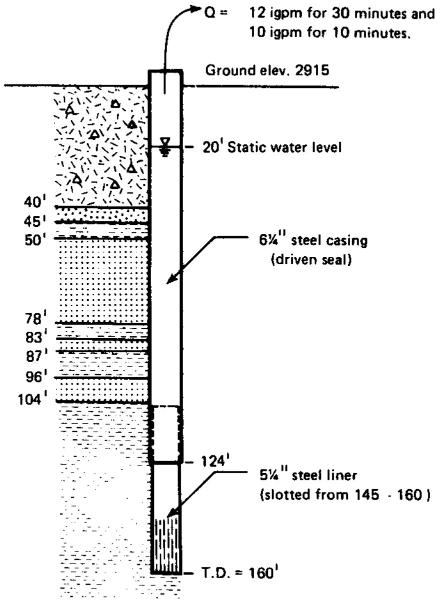
APPENDIX D: Selected Aquifer Test Analyses

SYMBOLS USED IN GEOLOGIC STRIP LOGS

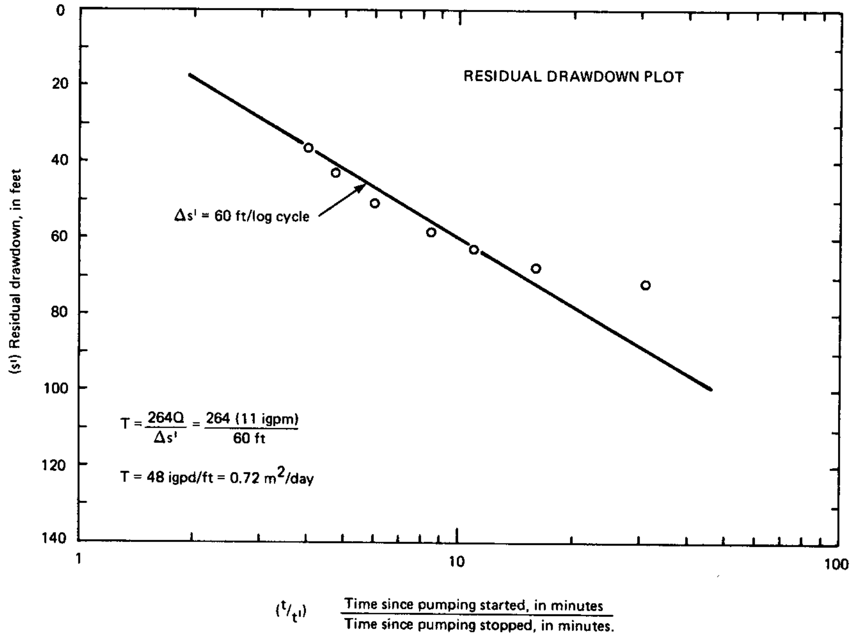




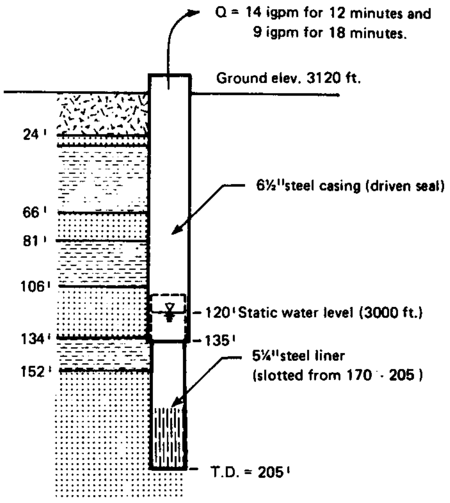
LITHOLOG AND COMPLETION DETAILS



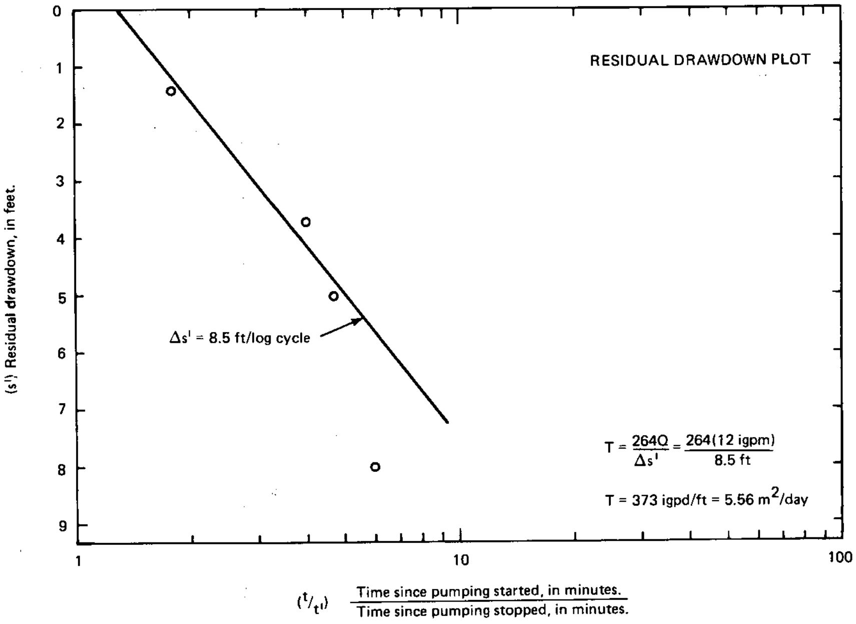
Well No. 33.5: 11-28-35-24W4

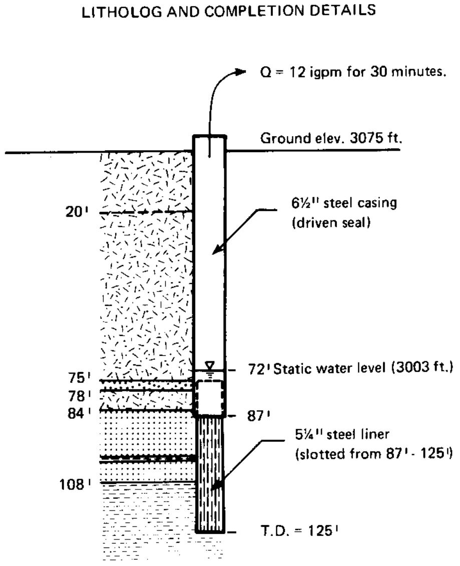


LITHOLOG AND COMPLETION DETAILS

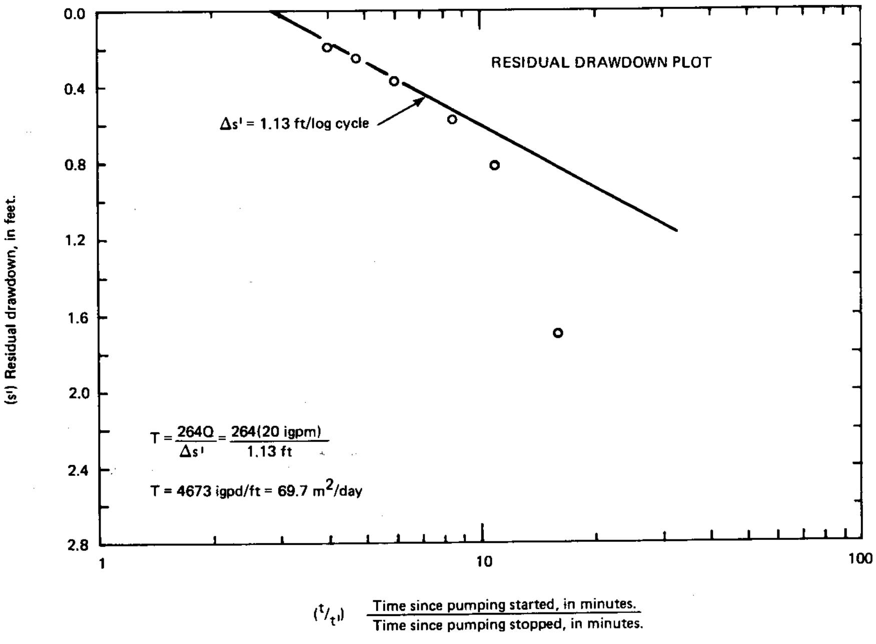


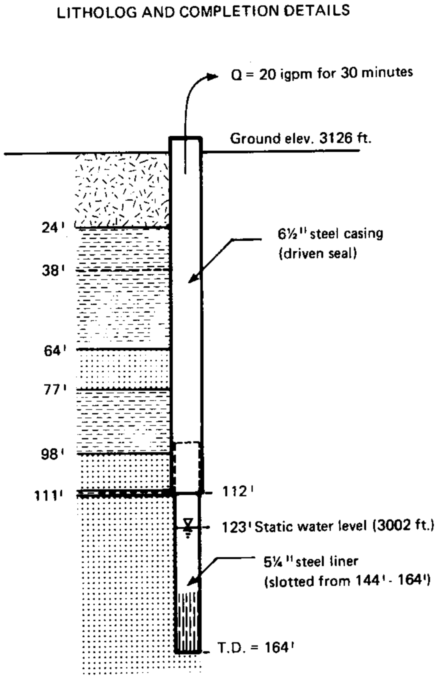
Well No. 57: 13-13-35-25W4



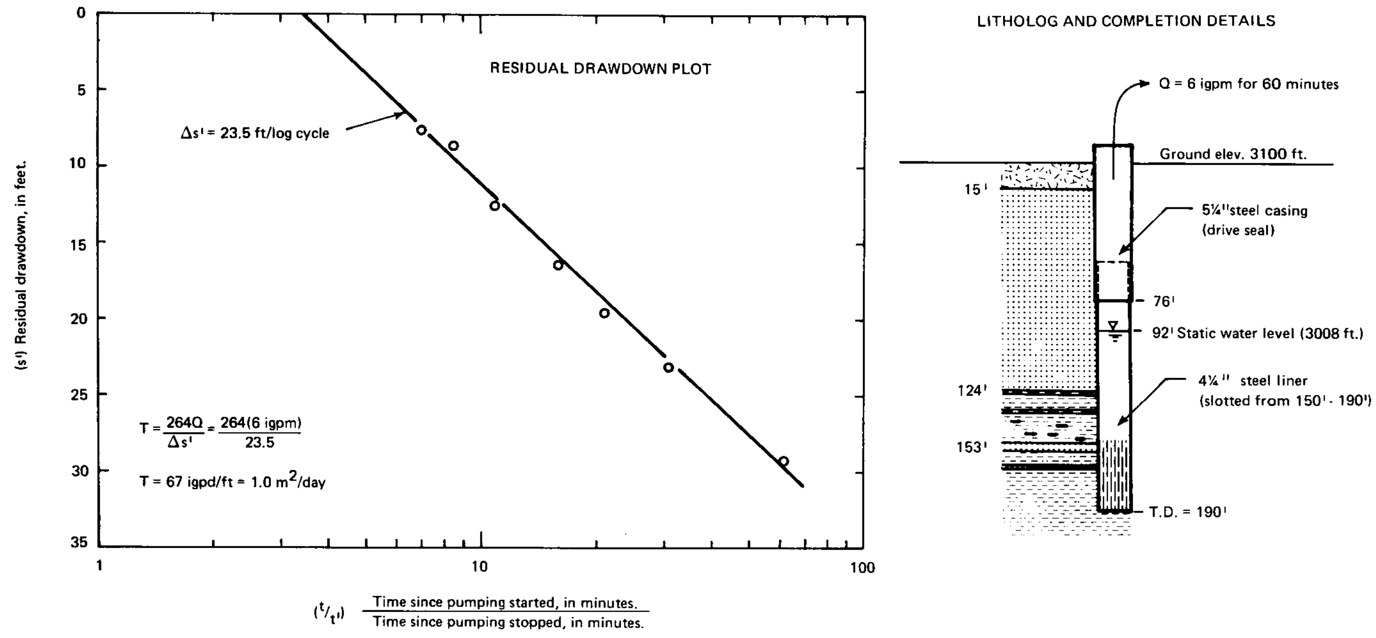


Well No. 61: 1-17-35-25W4

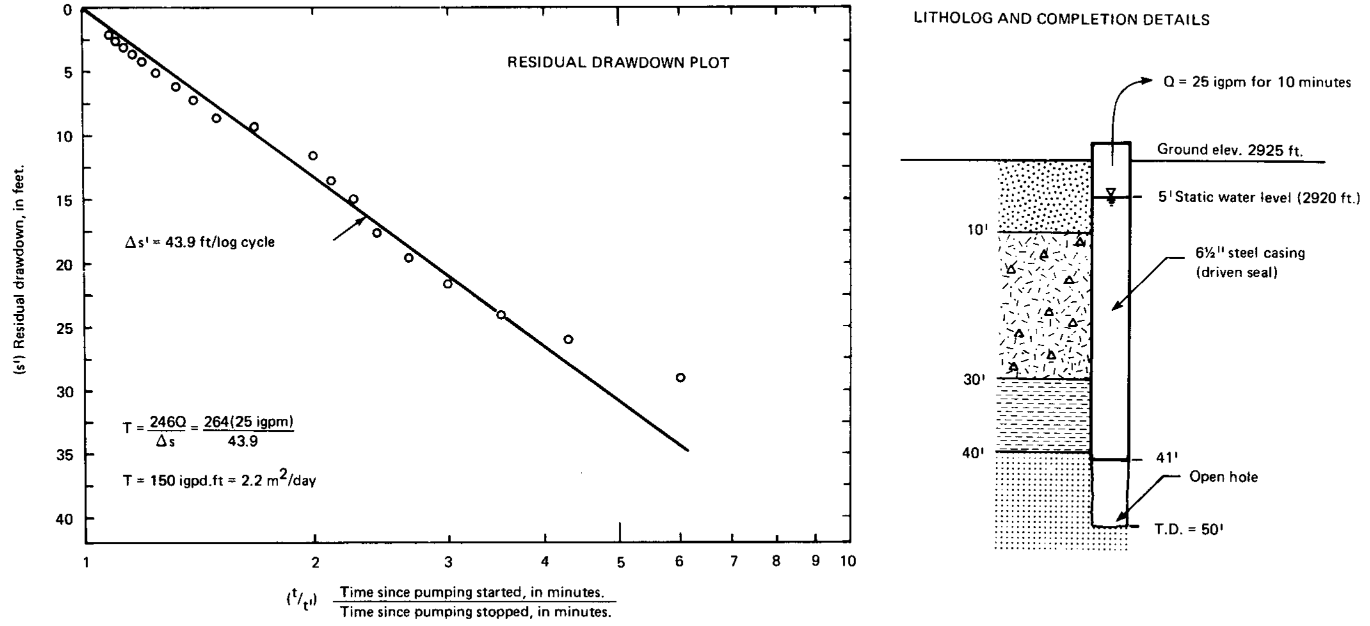




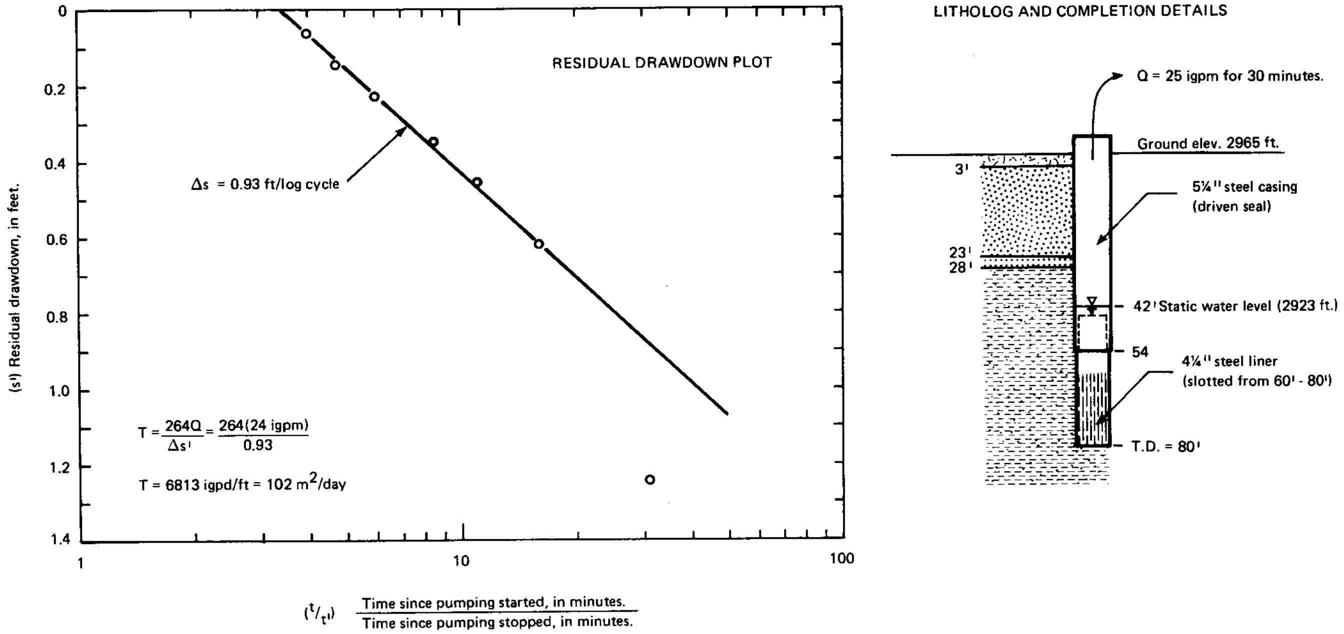
Well No. 71: 9-27-35-25W4



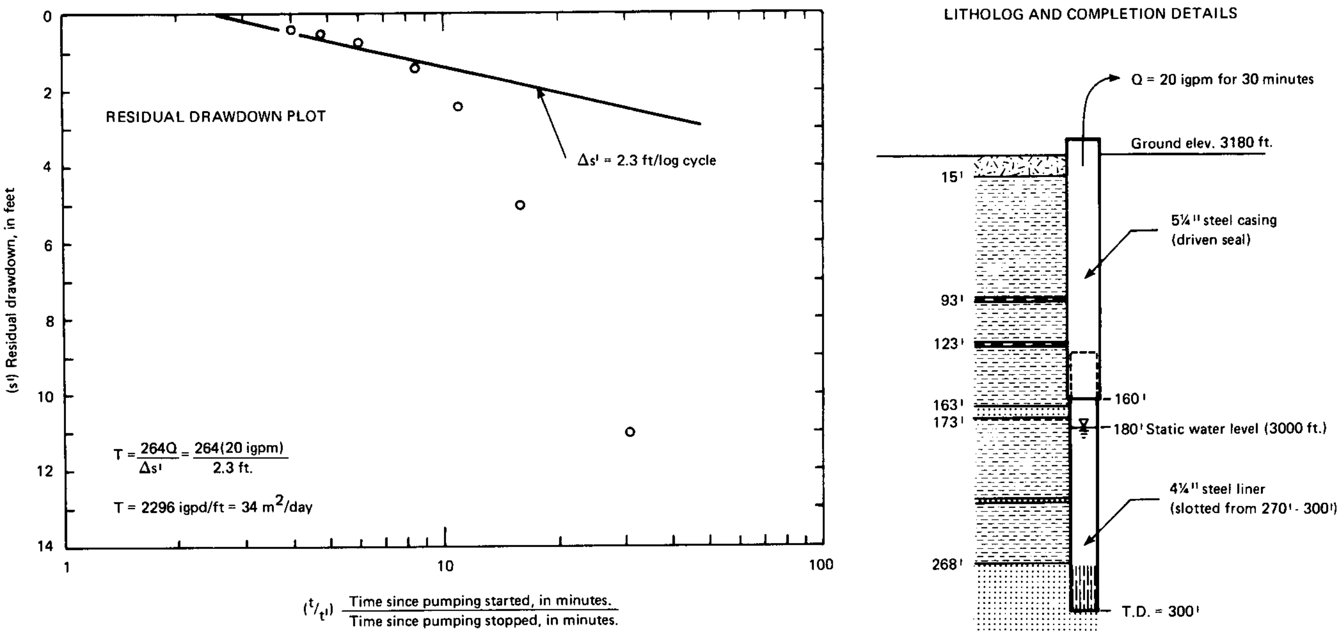
Well No. 83: 13-2-36-24W4



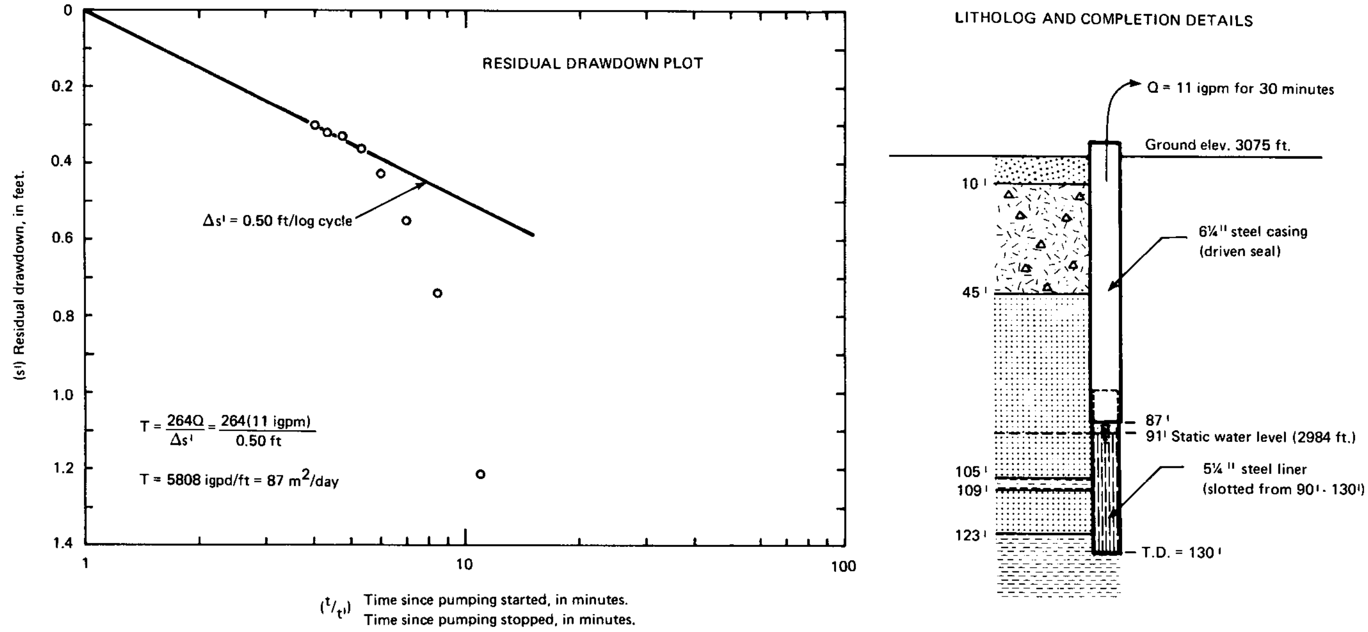
Well No. 96: 16-6-36-24W4



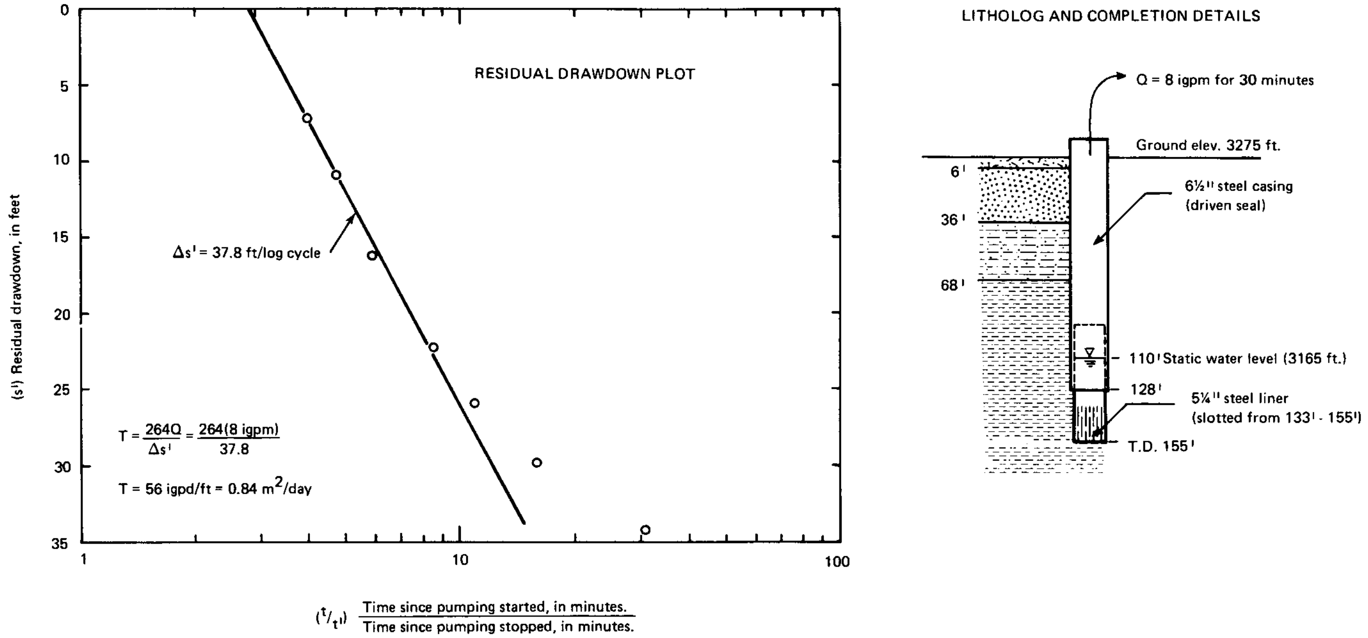
Well No. 110: 4-18-36-24W4



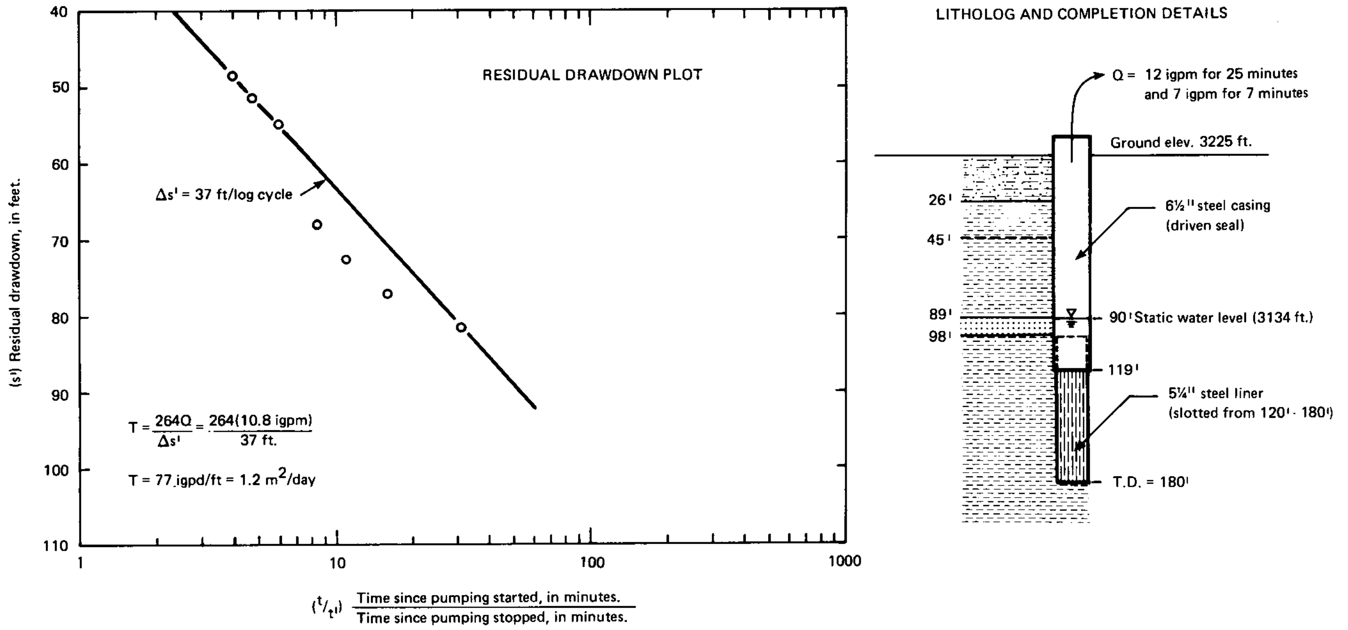
Well No. 138: 2-28-36-24W4



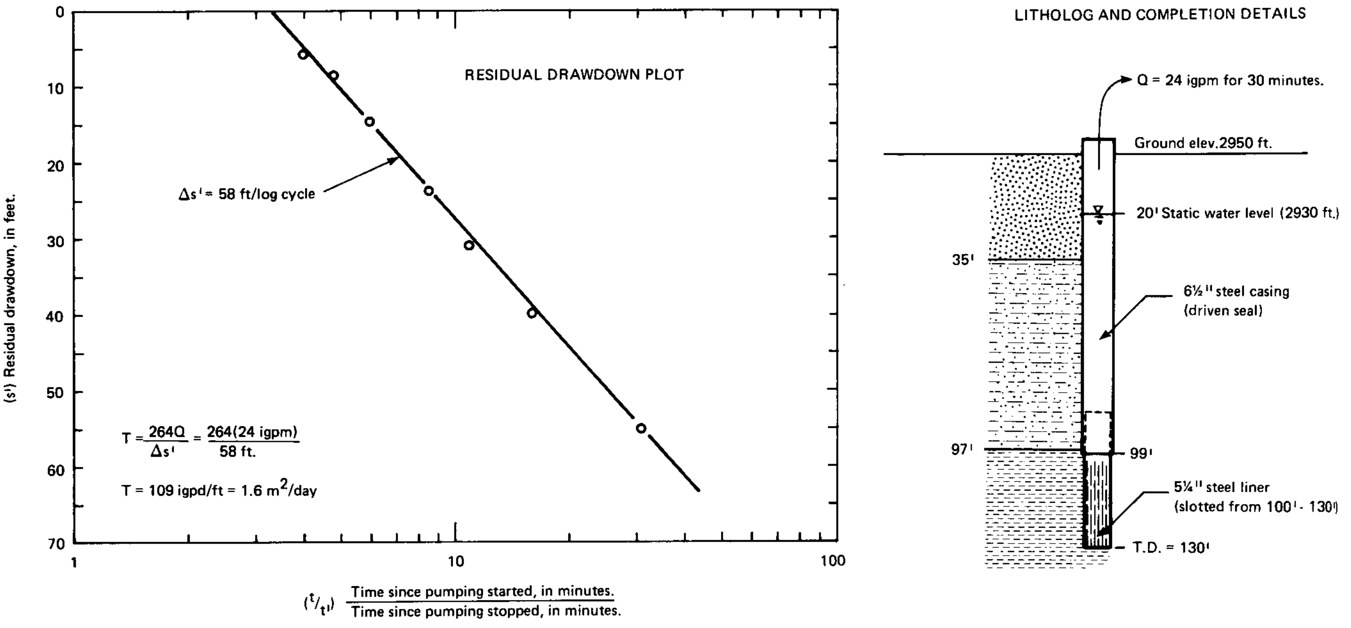
Well No. 151: 12-33-36-24W4



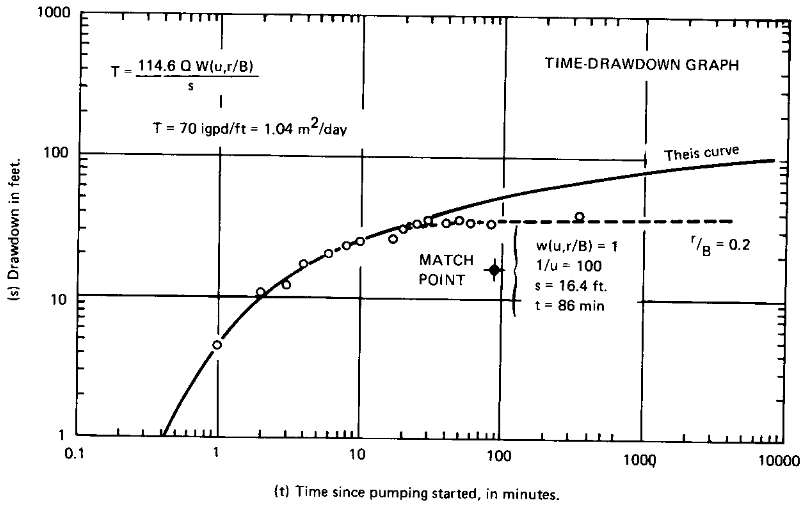
Well No. 162: 16-8-36-25W4

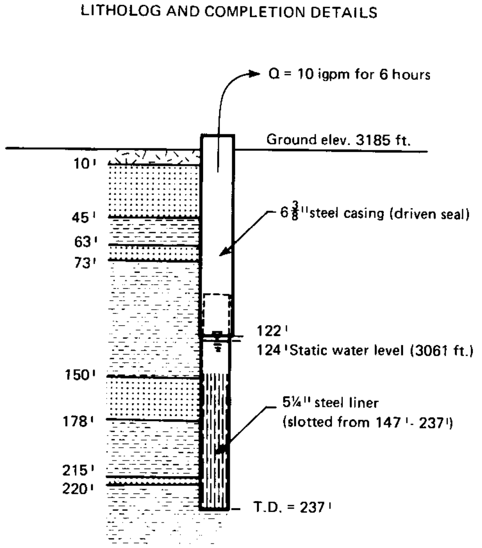


Well No. 165: 5-9-36-25W4

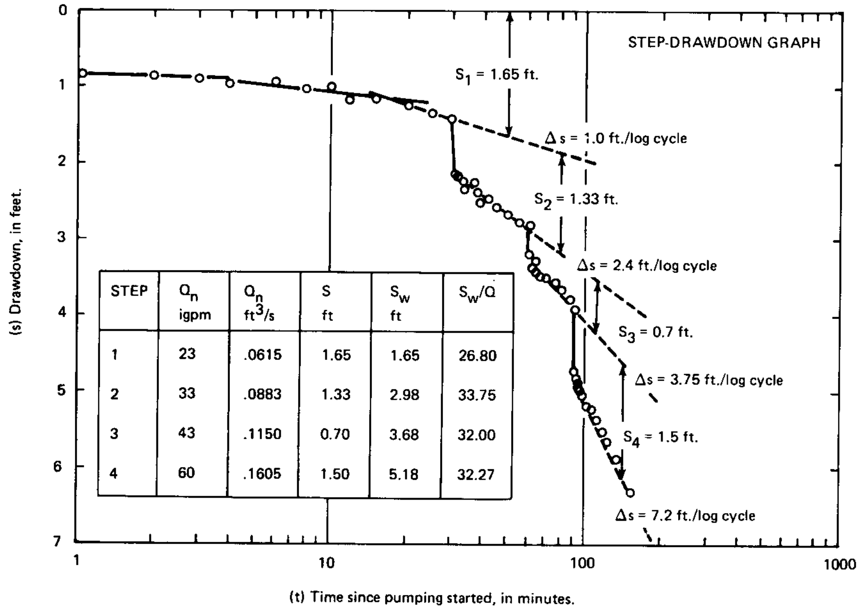


Well No. 317: 6-24-37-25W4

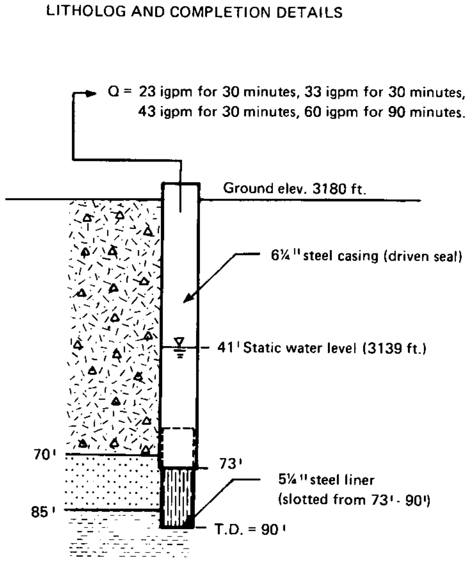




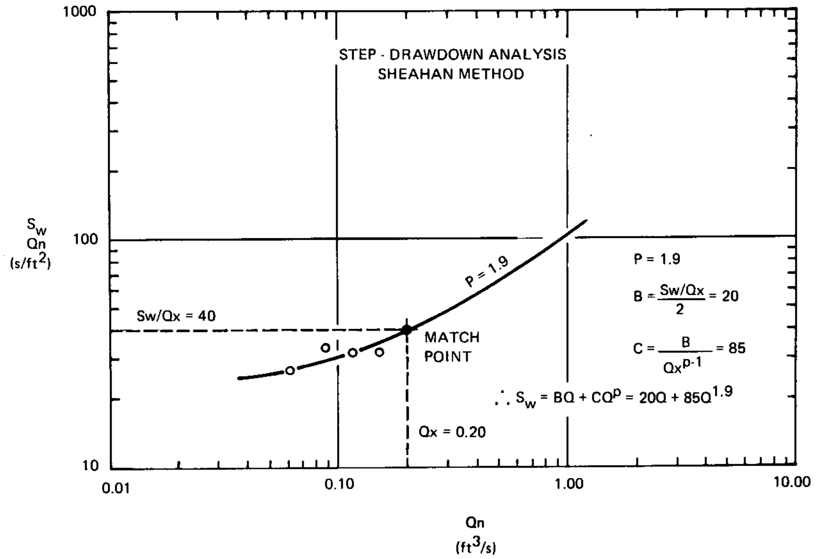
Well No. 330: 16-4-37-26W4

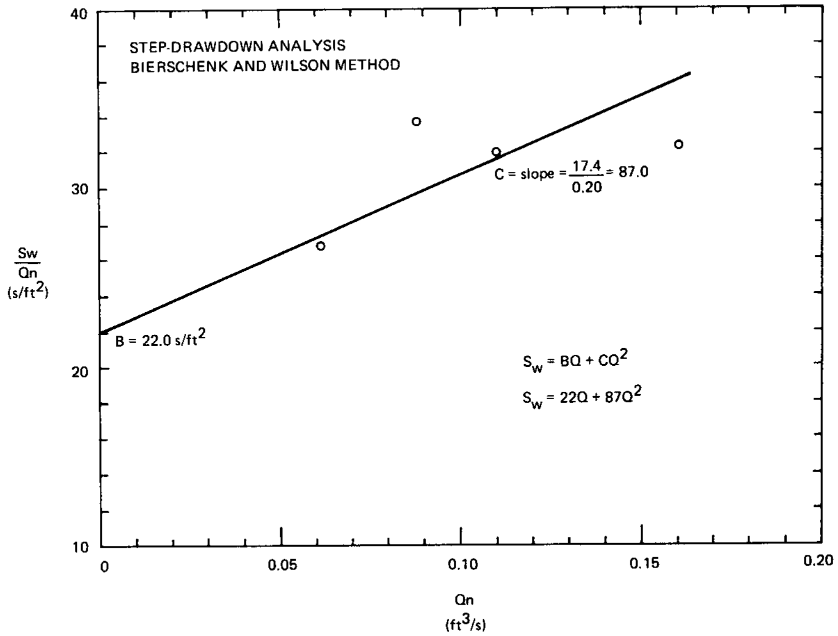


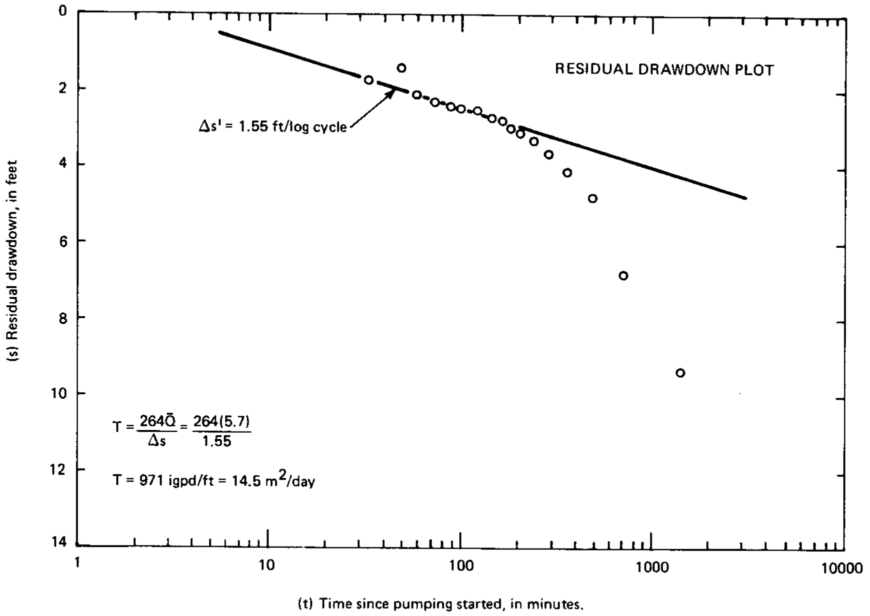
STEP	Q_n igpm	Q_n ft³/s	S ft	S_w ft	S_w/Q
1	23	.0615	1.65	1.65	26.80
2	33	.0883	1.33	2.98	33.75
3	43	.1150	0.70	3.68	32.00
4	60	.1605	1.50	5.18	32.27

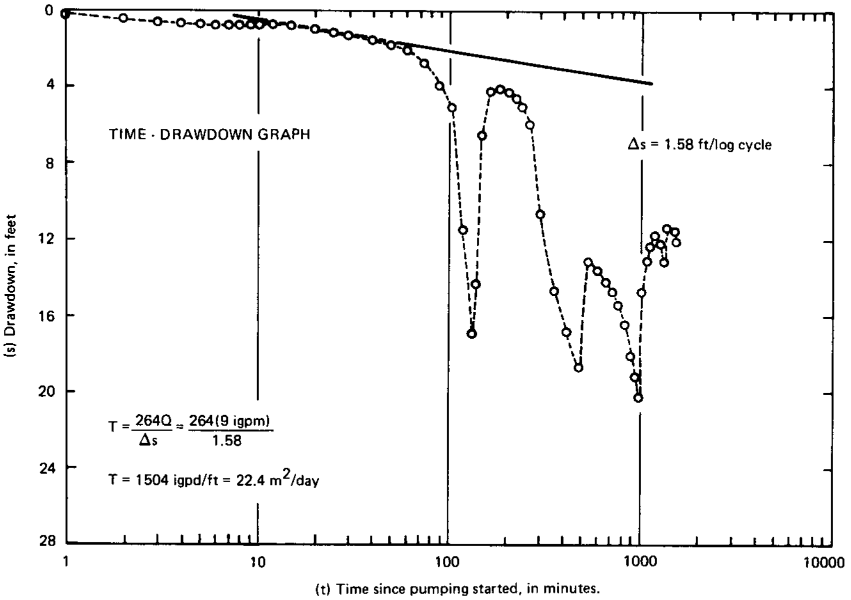


Well No. 335.5: 16-10-37-26W4

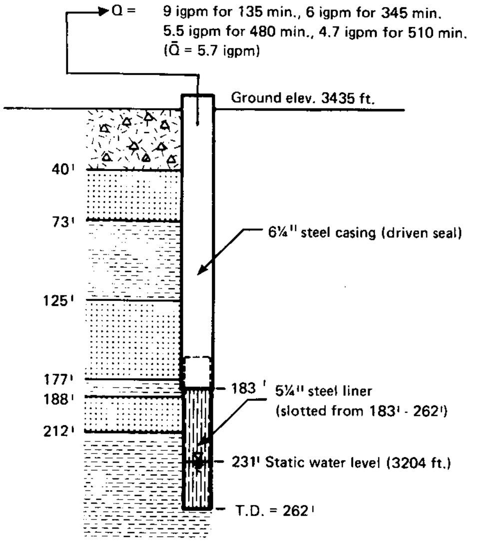

STEP - DRAWDOWN ANALYSIS
SHEAHAN METHOD
1000
100
10
Sw/Qn (s/ft²)
0.01
0.10
1.00
10.00
Qn (ft³/s)
Sw/Qx = 40
P = 1.9
MATCH POINT
Qx = 0.20
P = 1.9
B = Sw/Qx / 2 = 20
C = B / Qx^(P-1) = 85
∴ Sw = BQ + CQ^P = 20Q + 85Q^1.9


STEP-DRAWDOWN ANALYSIS
BIERSCHENK AND WILSON METHOD
40
30
20
10
Sw/Qn (s/ft²)
0
0.05
0.10
0.15
0.20
Qn (ft³/s)
C = slope = 17.4/0.20 = 87.0
B = 22.0 s/ft²
Sw = BQ + CQ²
Sw = 22Q + 87Q²





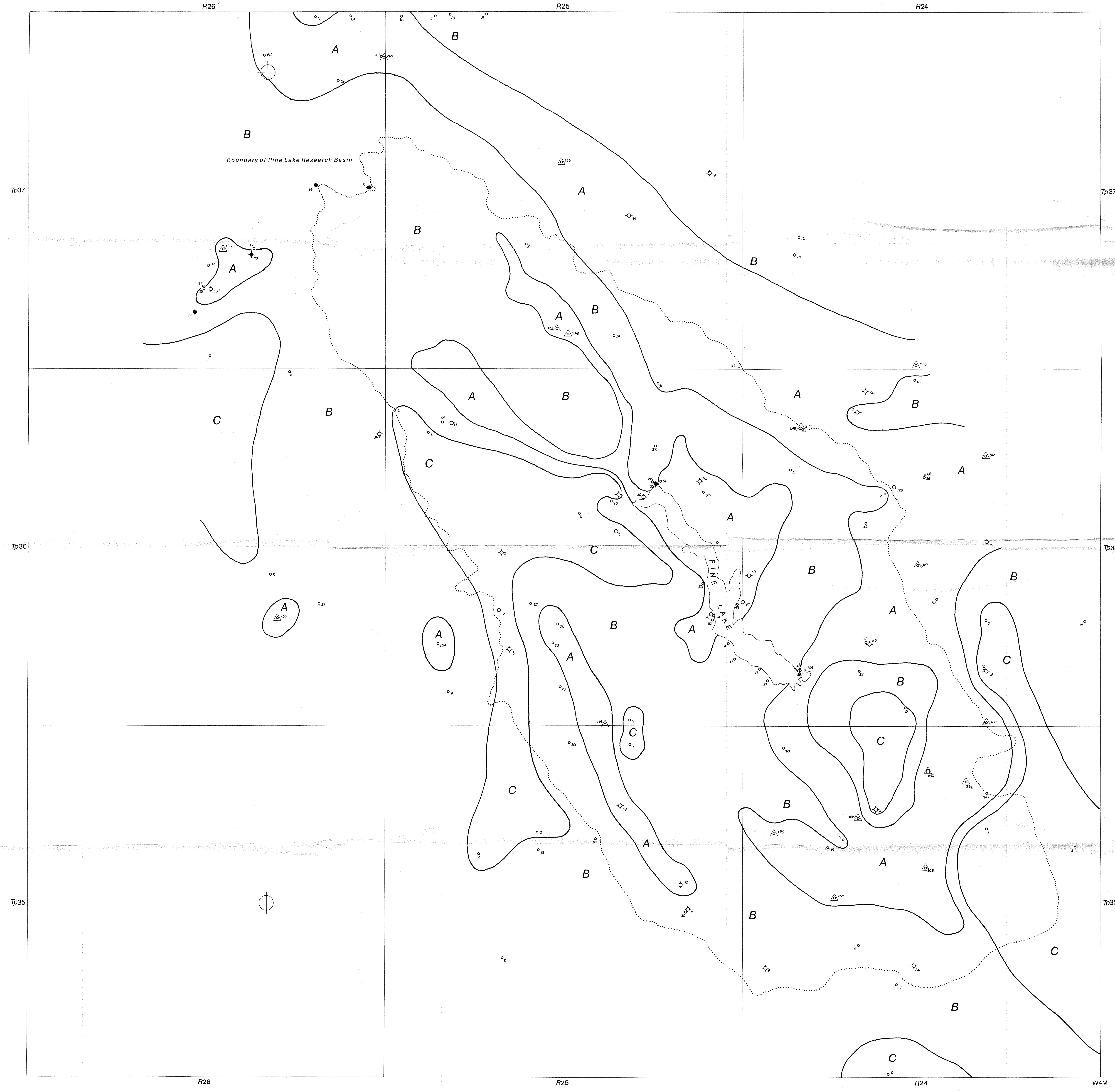
LITHOLOG AND COMPLETION DETAILS



Well No. 343: 1-23-37-26W4

FIGURE 45

GROUNDWATER PROBABILITY MAP
PINE LAKE RESEARCH BASIN



LEGEND

CONTROL POINTS: yield based upon:
- pump test .... ◆
- bail test .... ◇
- apparent transmissivity .... ○

AVERAGE MAXIMUM WELL YIELD

A	greater than 25 igpm
B	5 - 25 igpm
C	1 - 5 igpm

SCALE 1 : 50,000

Garven, G. (1980), M.S. Thesis, University of Arizona

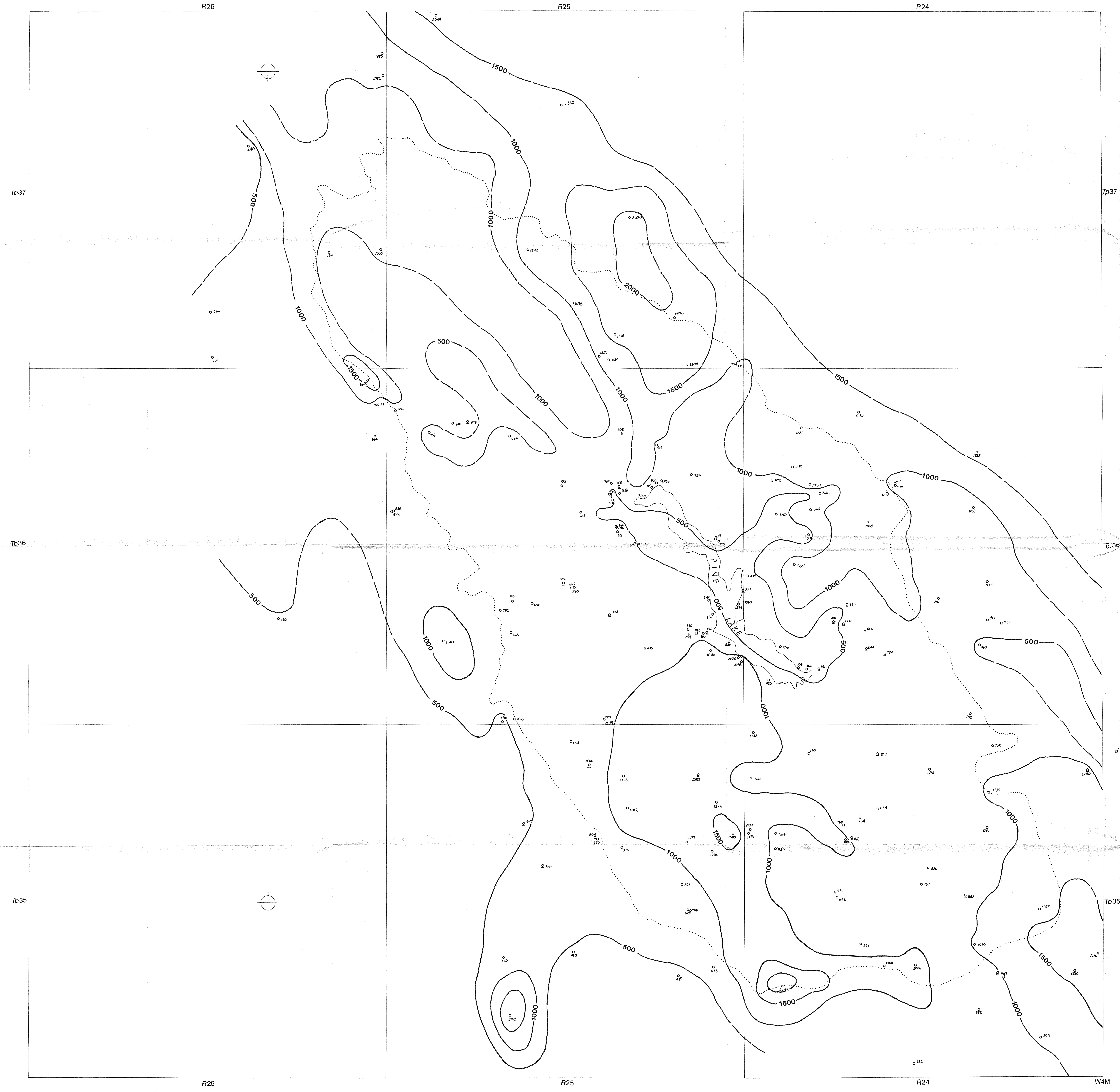


FIGURE 44

DISTRIBUTION OF TOTAL DISSOLVED SOLIDS

PINE LAKE RESEARCH BASIN

LEGEND

Well Control Point ○

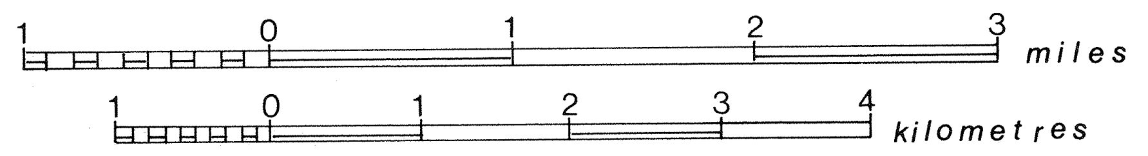
Spring Control Point ♀

Total Dissolved Solids Contour (mg/l); Defined, Assumed — 500 —

CONTOUR INTERVAL = 500 mg/l

Boundary of Pine Lake Research Basin

SCALE 1 : 50,000



Garven, G. (1980), M.S. Thesis, University of Arizona

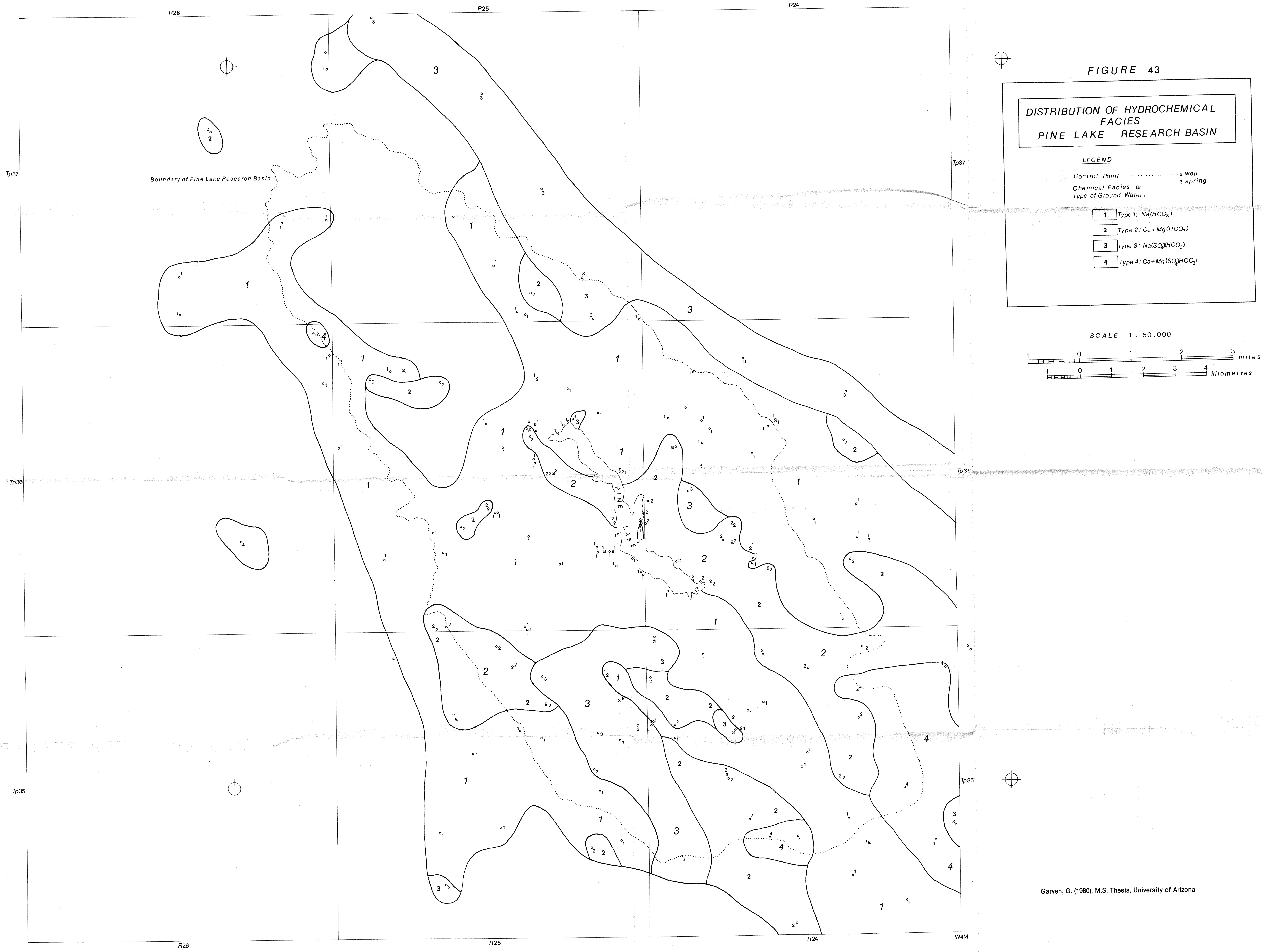


FIGURE 43

DISTRIBUTION OF HYDROCHEMICAL FACIES PINE LAKE RESEARCH BASIN

Garven, G. (1980), M.S. Thesis, University of Arizona

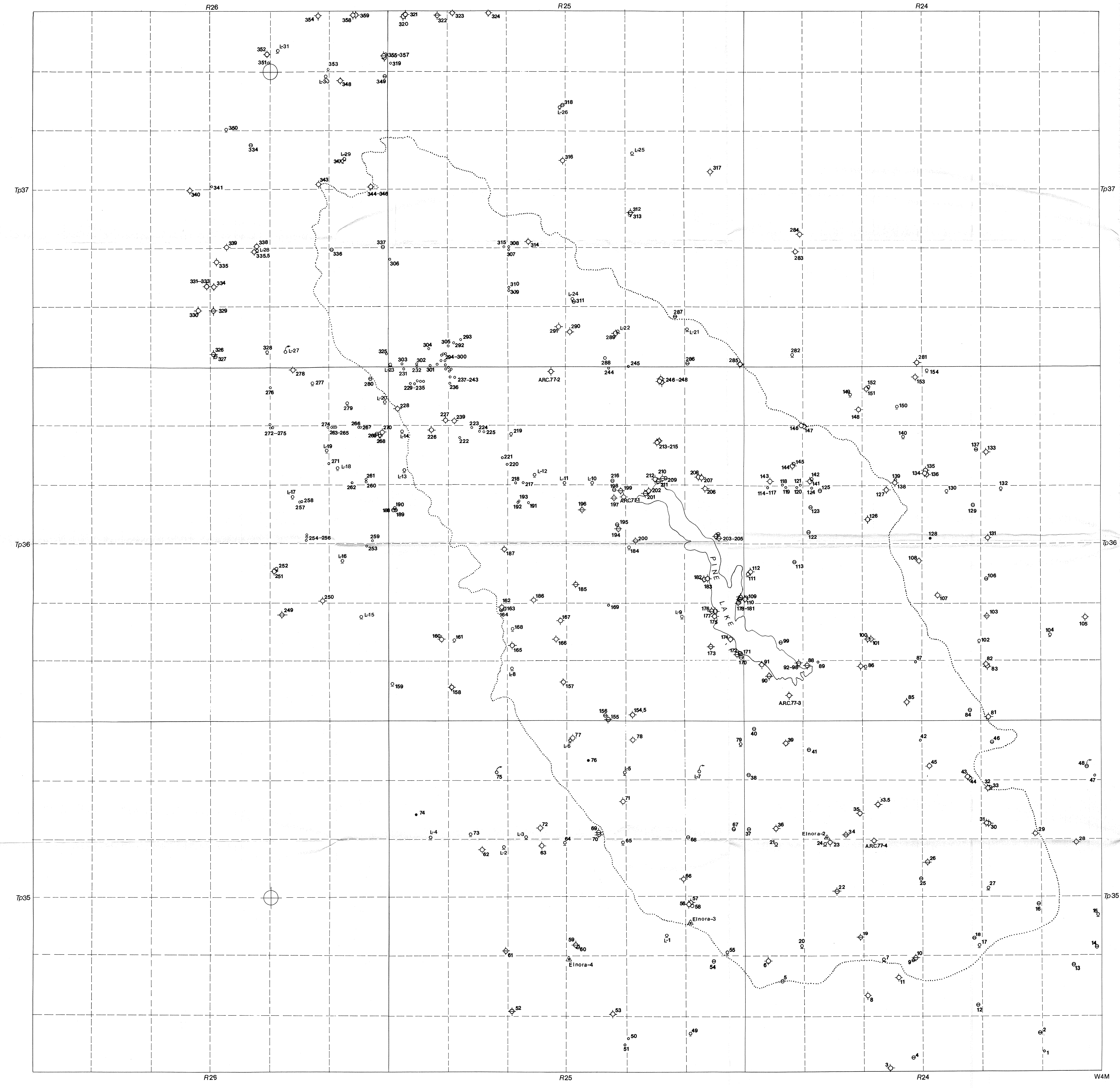


FIGURE 3

LOCATION MAP OF WELL DATA
PINE LAKE RESEARCH BASIN

LEGEND

- ◈ Complete driller's report, including water chemistry analysis.
- ◇ Driller's report.
- ▲ Observation well, equipped with automatic water-level recorder.
- ⊖ Water chemistry analysis only.
- ♀ Well inventory data only.
- ↄ Spring reported
- ○ Flowing seismic shot hole report.
- ● Oil or gas well electric log on file.
- ⋯ Outline of basin.

Data Sources: Groundwater Data Centre
Alberta Research Council

and

Latour (1948)

(see Appendix A for index number data)

SCALE 1 : 50,000

1 0 1 2 3 miles

1 0 1 2 3 4 kilometres

Garven, G. (1980), M.S. Thesis, University of Arizona

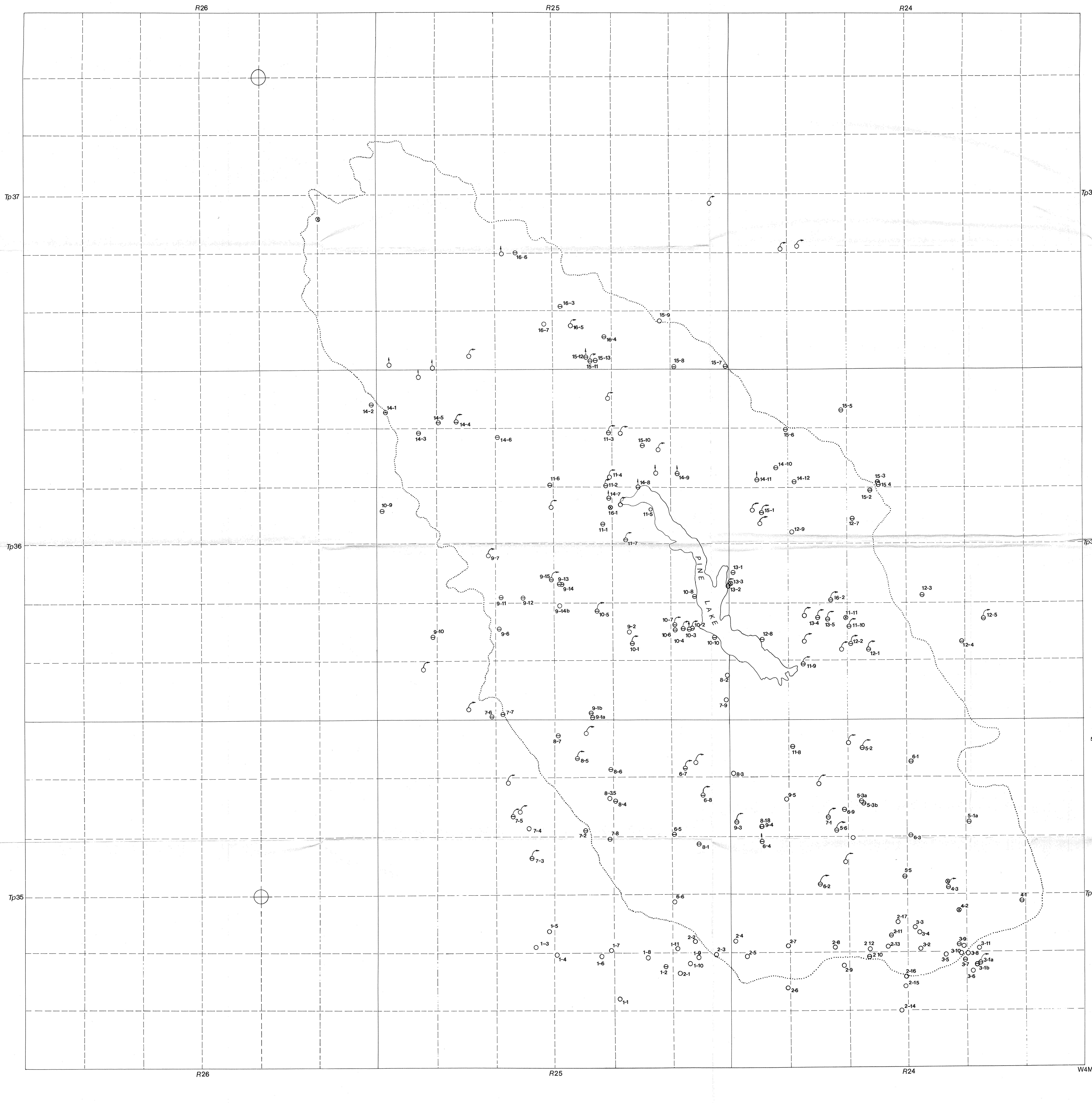


FIGURE 4

LOCATION MAP OF FIELD OBSERVATIONS
(Summer, 1978)

PINE LAKE RESEARCH BASIN

LEGEND

⊖ General feature; horizontal slash indicates water sample taken.

Flowing well.

Spring.

⊗ Bedrock exposure.

Boundary of Pine Lake Research Basin

(see Appendix A and B for index number data)

SCALE 1 : 50,000

1 0 1 2 3 miles

1 0 1 2 3 4 kilometres

Garven, G. (1980), M.S. Thesis, University of Arizona

FIGURE 19
GEOLOGICAL SECTION C-C*

LEGEND

- ▨ DRIFT
- ▨ SANDSTONE
- ☐ SILTSTONE and SHALE
- | Structure test hole electric log
- ‖ Water well litholog

(see Appendix A and C for index number data)

Garven, G. (1980), M.S. Thesis, University of Arizona

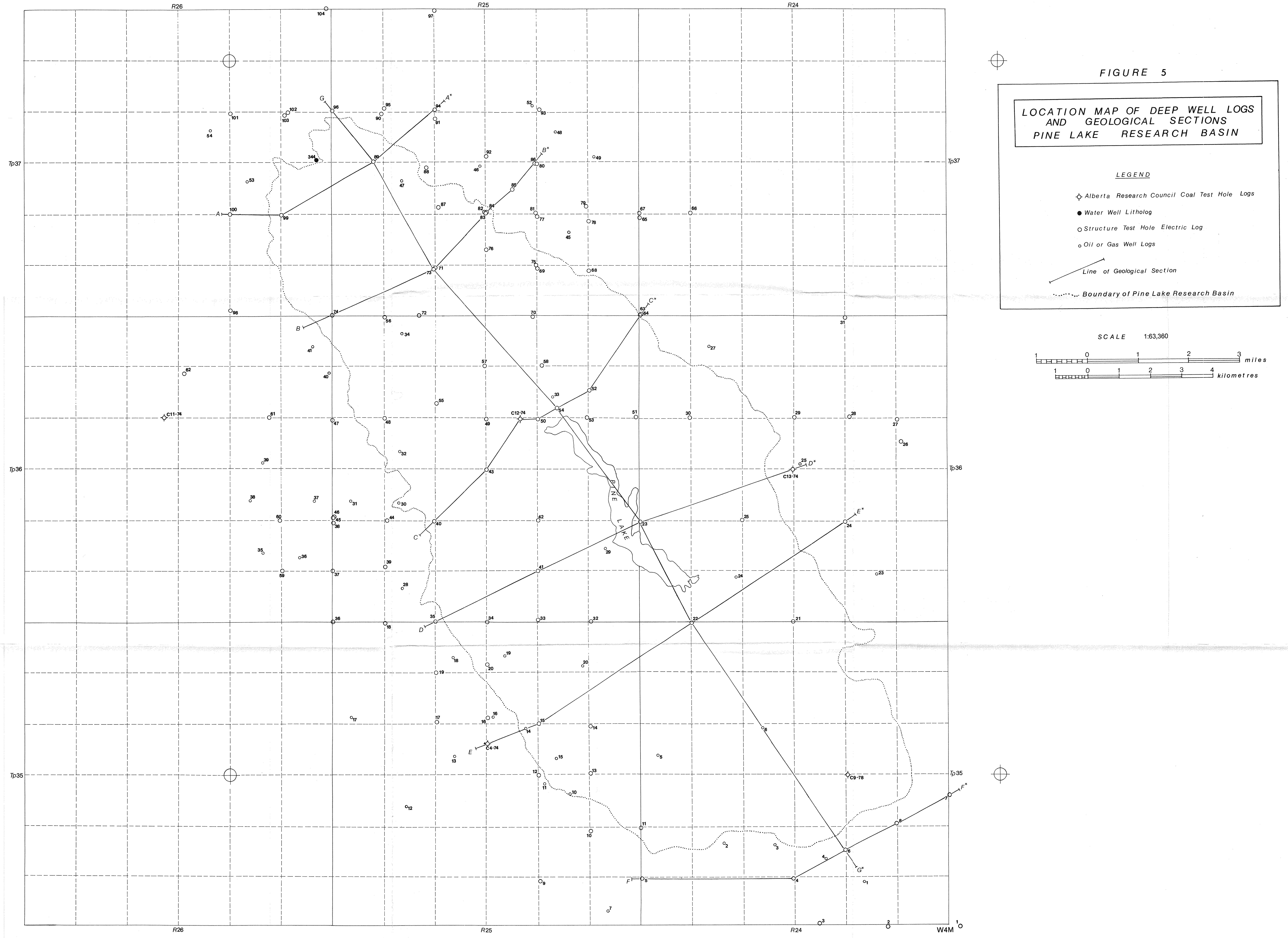


FIGURE 5

LOCATION MAP OF DEEP WELL LOGS AND GEOLOGICAL SECTIONS PINE LAKE RESEARCH BASIN

Garven, G. (1980), M.S. Thesis, University of Arizona

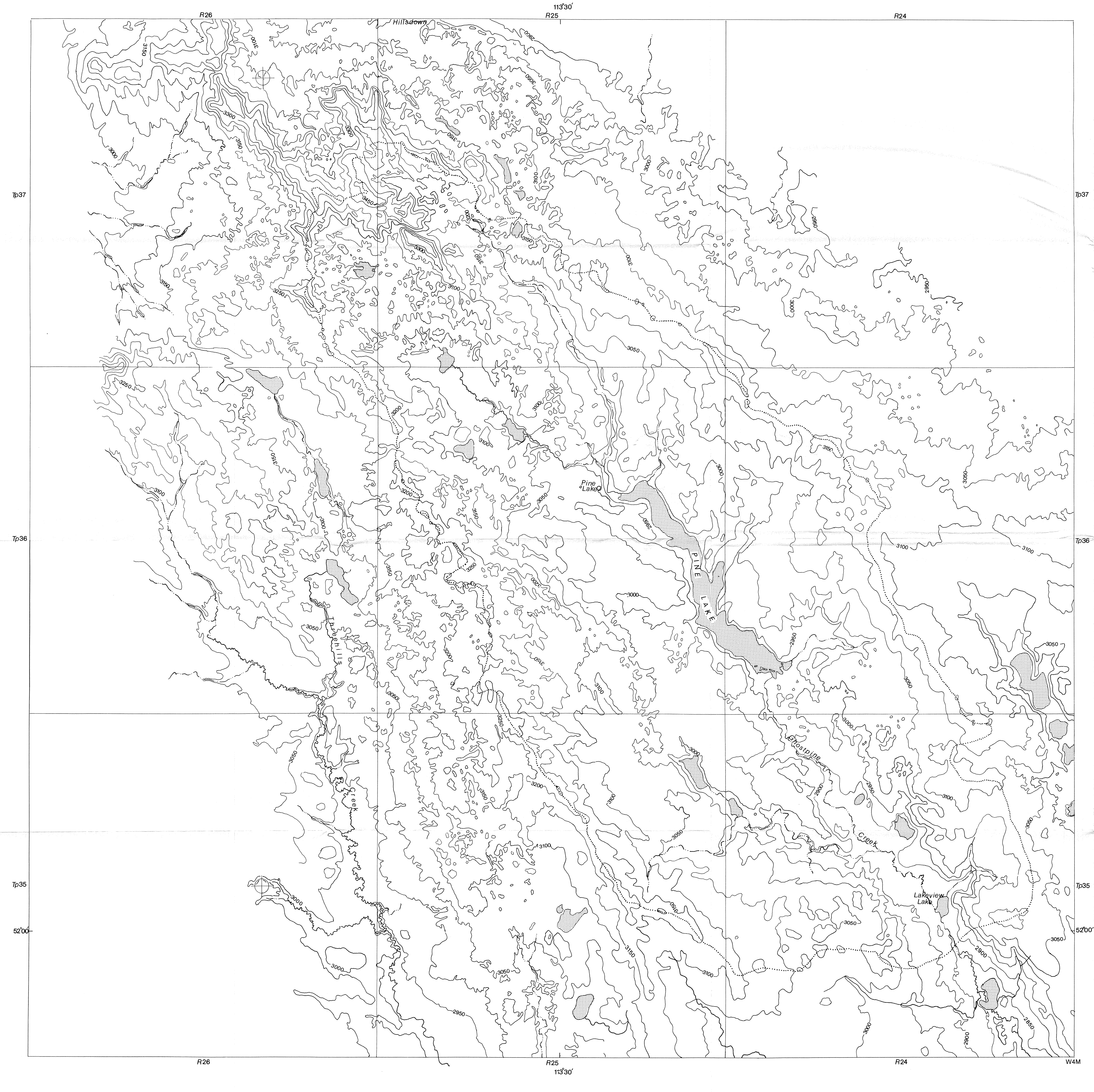


FIGURE 6

TOPOGRAPHY and DRAINAGE
PINE LAKE RESEARCH BASIN

LEGEND

3200 Topographic elevation contour (in feet above mean sea level)

Boundary of Pine Lake Research Basin

(Contour interval = 50 feet)

SCALE 1 : 50,000

1 0 1 2 3 miles

1 0 1 2 3 4 kilometres

Garven, G. (1980), M.S. Thesis, University of Arizona

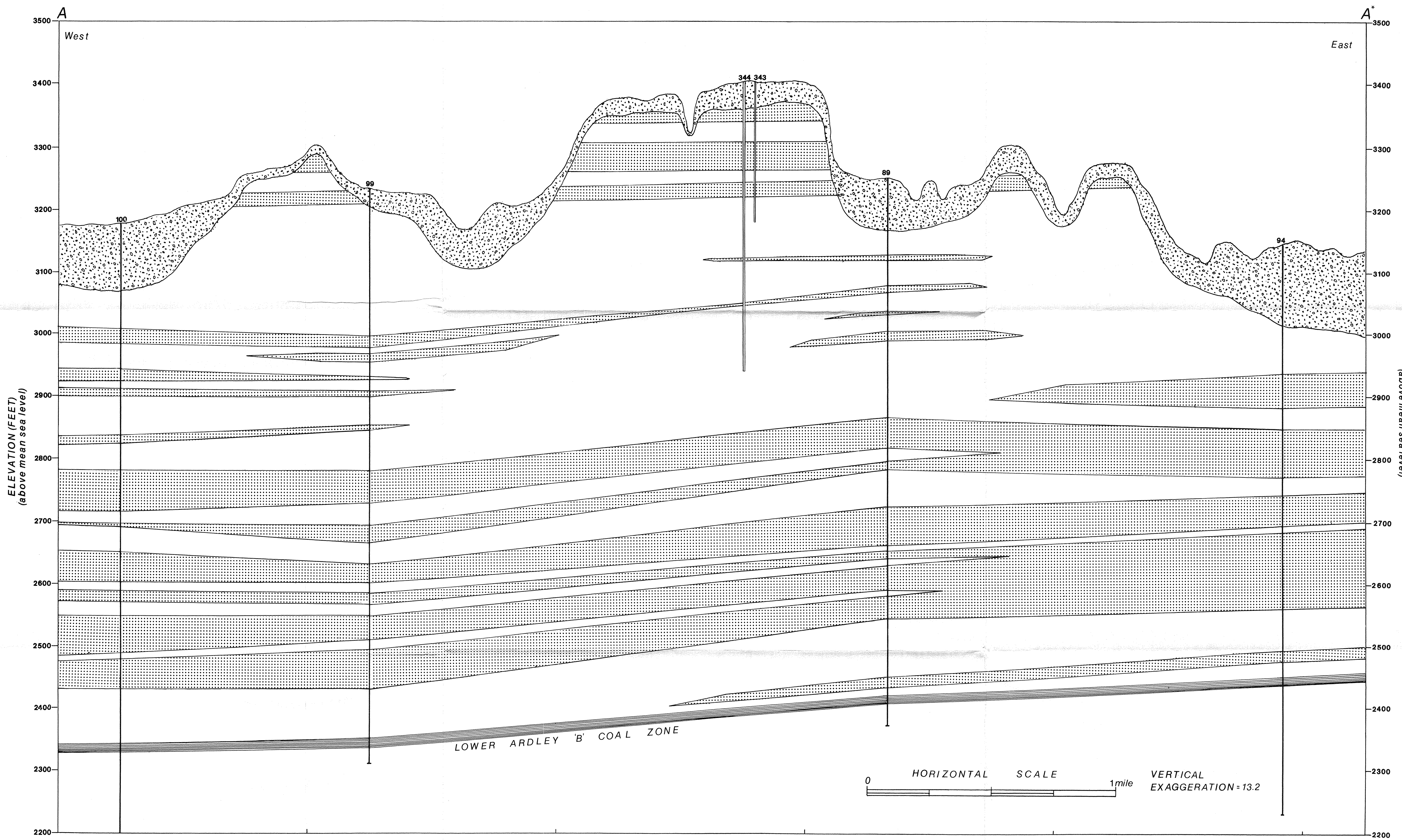


FIGURE 17
GEOLOGICAL SECTION A-A*

(see Appendix A for index number data)

Garven, G. (1980), M.S. Thesis, University of Arizona

FIGURE 20
GEOLOGICAL SECTION D-D*

(see Appendix A and C for index number data)

Garven, G. (1980), M.S. Thesis, University of Arizona

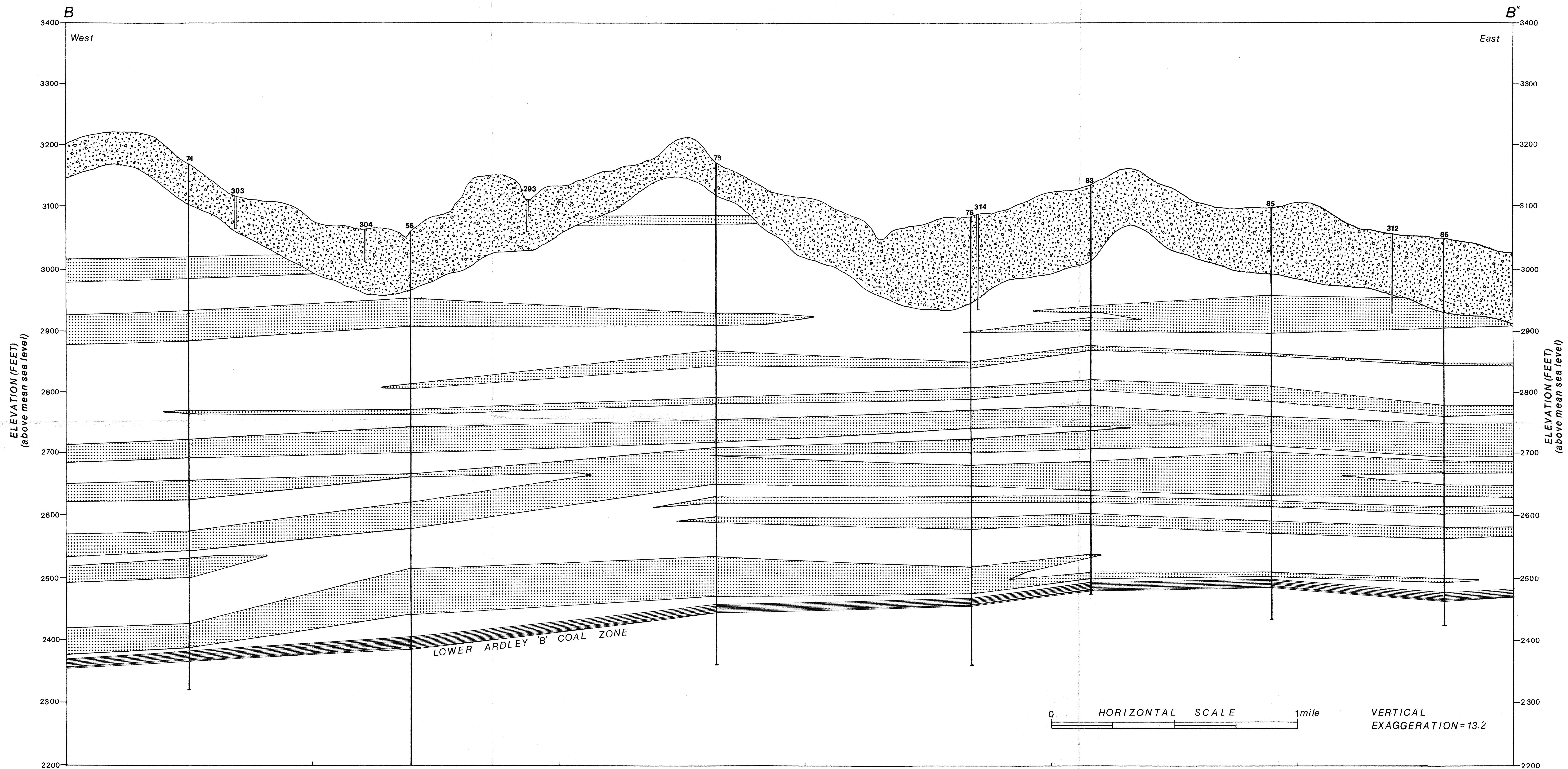


FIGURE 18
GEOLOGICAL SECTION B-B*

(see Appendix A and C for index number data)

Garven, G. (1980), M.S. Thesis, University of Arizona

FIGURE 21
GEOLOGICAL SECTION E-E*

(see Appendix A and C for index number data)

Garven, G. (1980), M.S. Thesis, University of Arizona

FIGURE 22
GEOLOGICAL SECTION F-F*

(see Appendix A and C for index number data)

Garven, G. (1980), M.S. Thesis, University of Arizona

FIGURE 23
GEOLOGICAL SECTION G-G*

LEGEND

- ▨ DRIFT
- ▦ SANDSTONE
- ☐ SILTSTONE and SHALE
- Structure test hole electric log
- Oil or gas test hole radioactivity logs
- Water wel. litholog

(see Appendix A and C for index number data)

Garven, G. (1980), M.S. Thesis, University of Arizona

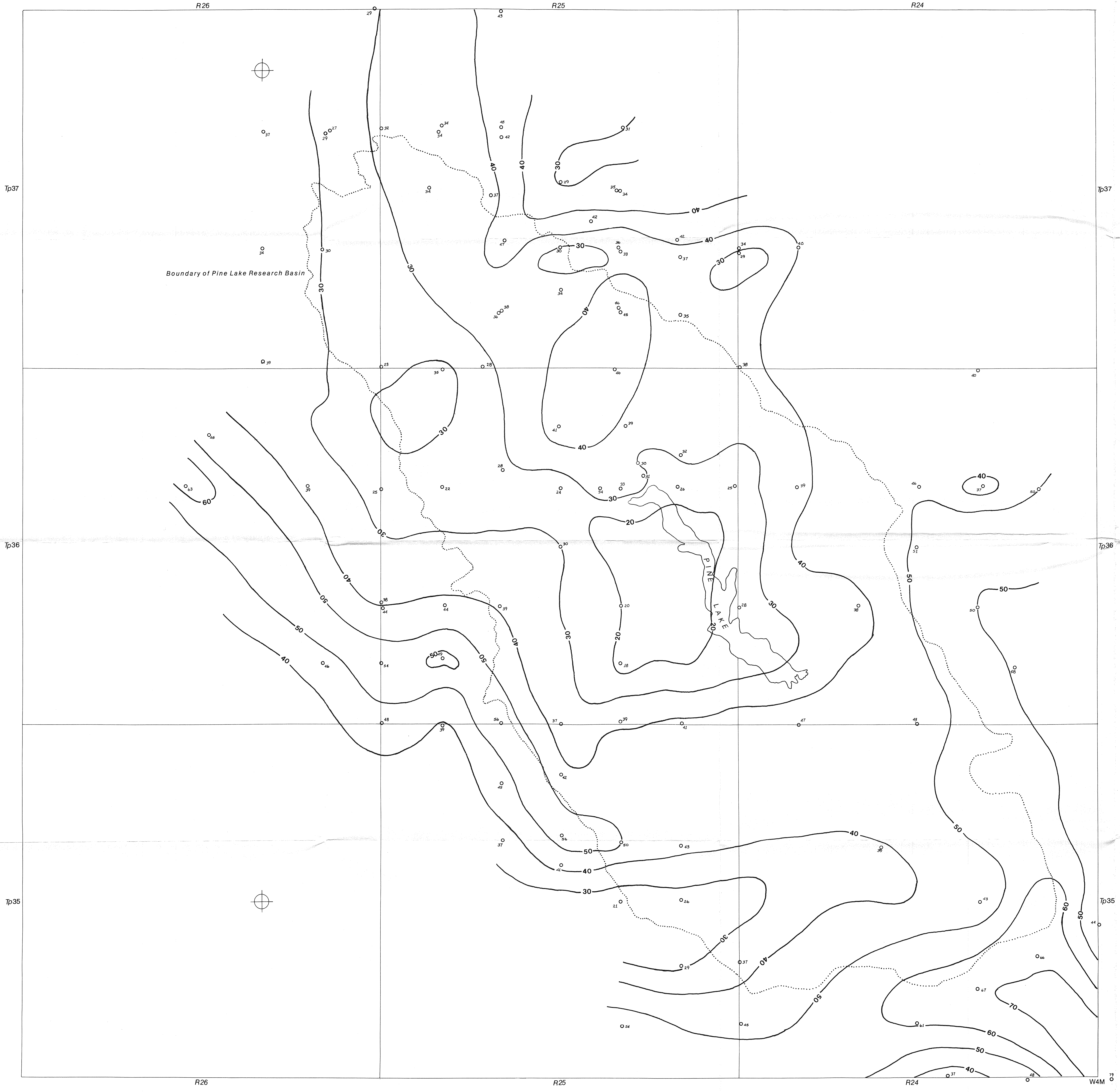


FIGURE 24

PERCENTAGE SANDSTONE MAP OF THE PASKAPOO FM. ABOVE L. ARDLEY 'B' COAL PINE LAKE RESEARCH BASIN

LEGEND

CONTROL POINT ○

CONTOUR INTERVAL = 10 %

SCALE 1 : 50,000

1 0 1 2 3 miles

1 0 1 2 3 4 kilometres

Garven, G. (1980), M.S. Thesis, University of Arizona

FIGURE 25

STRUCTURE CONTOUR MAP ON TOP OF THE LOWER ARDLEY COAL ZONE (B) PINE LAKE BASIN

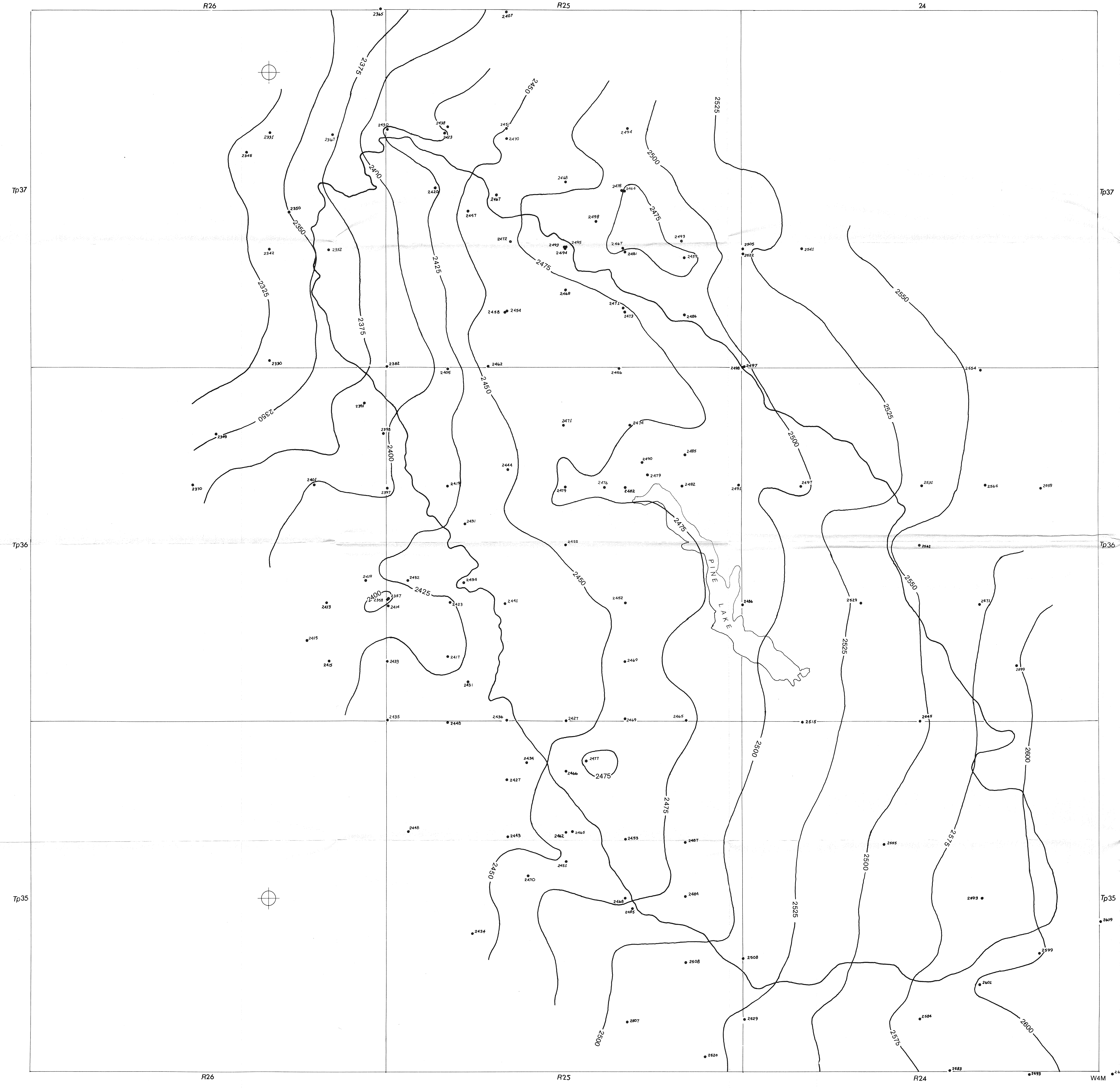
LEGEND

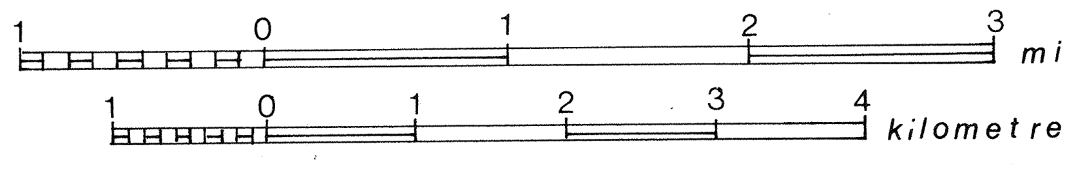
2497 Control Well

2550 Structure Contour Elevation (feet above mean sea level)

CONTOUR INTERVAL = 25 ft.

SCALE 1 : 50,000





Garven, G. (1980), M.S. Thesis, University of Arizona

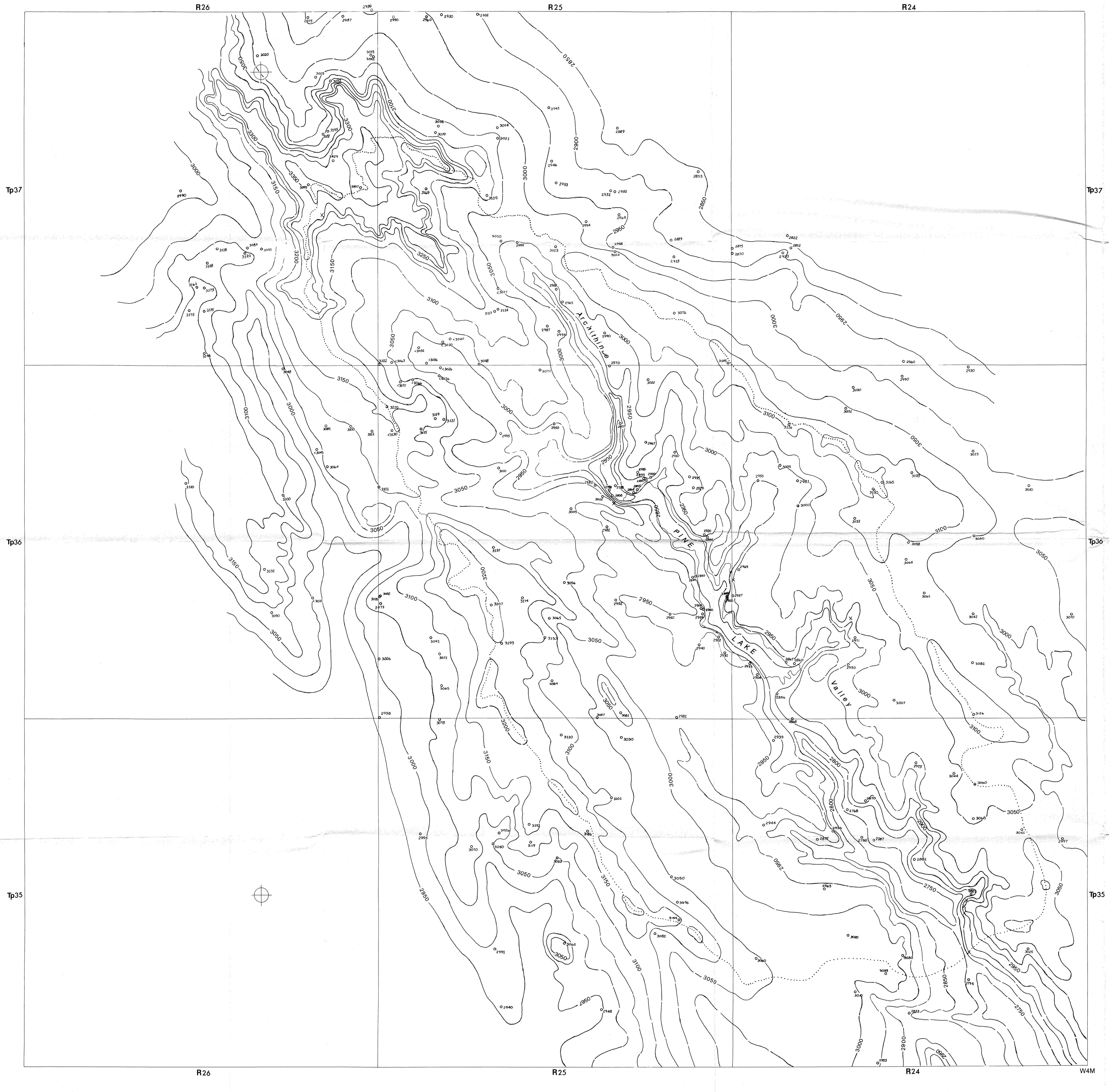


FIGURE 26

BEDROCK TOPOGRAPHY MAP
PINE LAKE RESEARCH BASIN

LEGEND

○ 2960 Control Point Elevation (ft.).

Bedrock Contour; defined, assumed.

CONTOUR INTERVAL = 50 ft.

Boundary of Pine Lake Research Basin

SCALE 1 : 50,000

1 0 1 2 3 miles

1 0 1 2 3 4 kilometres

Garven, G. (1980), M.S. Thesis, University of Arizona

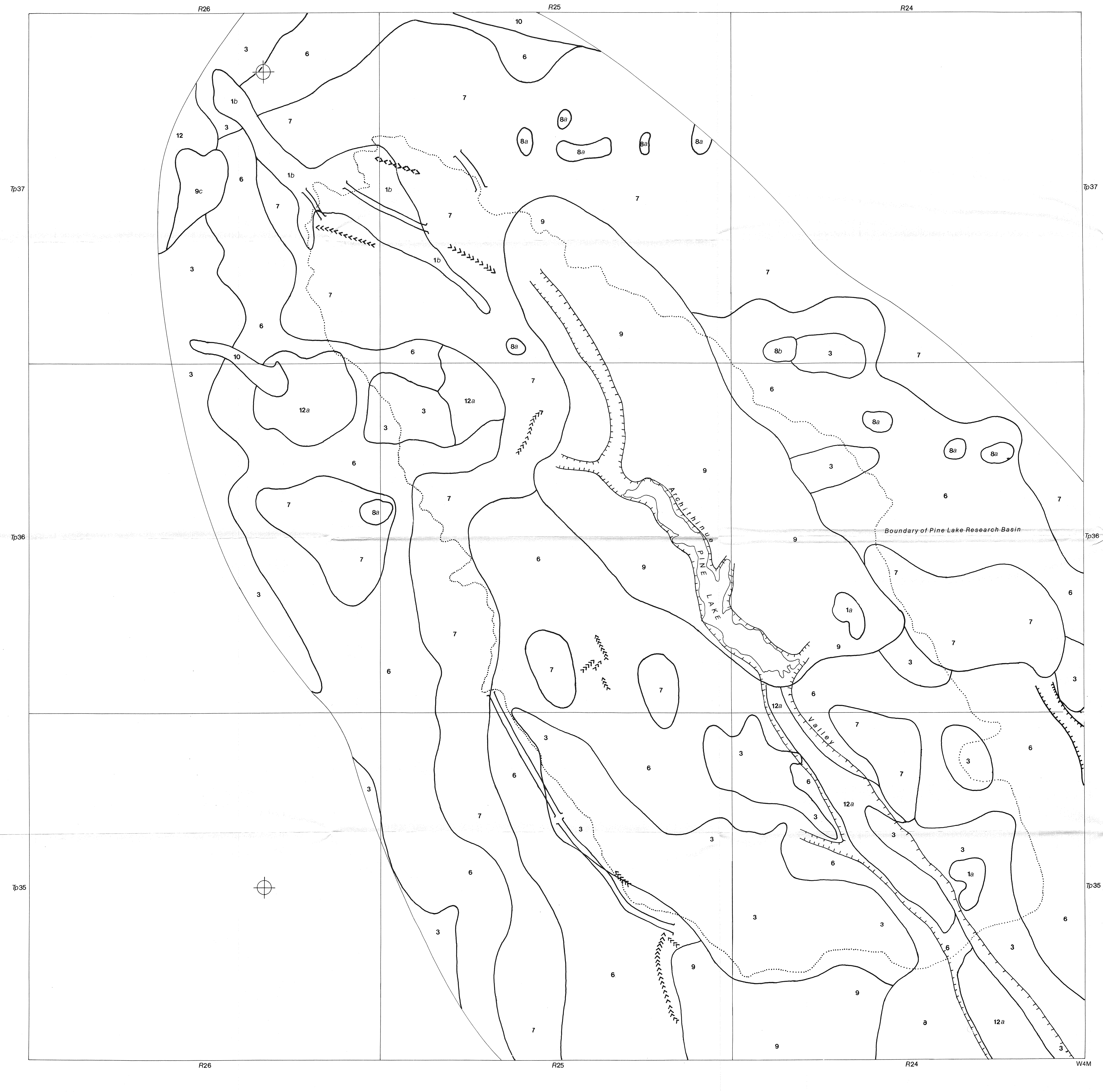


FIGURE 27

SURFICIAL GEOLOGY OF THE PINE LAKE RESEARCH BASIN

(after Stalker, 1960, and Holter, 1975)

LEGEND

QUATERNARY

PLEISTOCENE and RECENT

12	GLACIOLACUSTRINE DEPOSITS: 12a, sand and silt.

PLEISTOCENE

10	ALLUVIUM, FINE: sand, silt, clay; includes some slump, minor amounts of gravel and bedrock exposures
9	OUTWASH DEPOSITS · gravel, sand, silt, clay, till, some lacustrine material; 9c, chiefly gravel.
8	STAGNANT ICE DEPOSITS · till, clay, silt, sand, and gravel; 8a, moraine plateau, with local rim ridges of till; 8b, ice block depressions, with rim ridges of gravel, sand, silt, and till.
7	HUMMOCKY MORAINE: knob and kettle topography strongly developed; includes dead-ice and recession moraine, mainly till
6	HUMMOCKY MORAINE: knob and kettle topography moderately developed; includes dead-ice and recessional moraine, mainly till.
3	GROUND MORAINE: till, undulating to gently rolling plain.

TERTIARY

PALEOCENE

1	BEDROCK (Paleocene): sandstone, siltstone, and shale of the Paskapoo Fm., locally covered by thin slump, alluvium, or drift; 1a, exposed by post-glacial erosion; 1b, area of little or no Pleistocene and Recent deposition.

ESKER RIDGE: till, gravel, sand, silt, and clay (direction of flow defined, not defined) ....

WIND GAP ....

BURIED VALLEY ....

SCALE 1 : 50,000

Garven, G. (1980), M.S. Thesis, University of Arizona

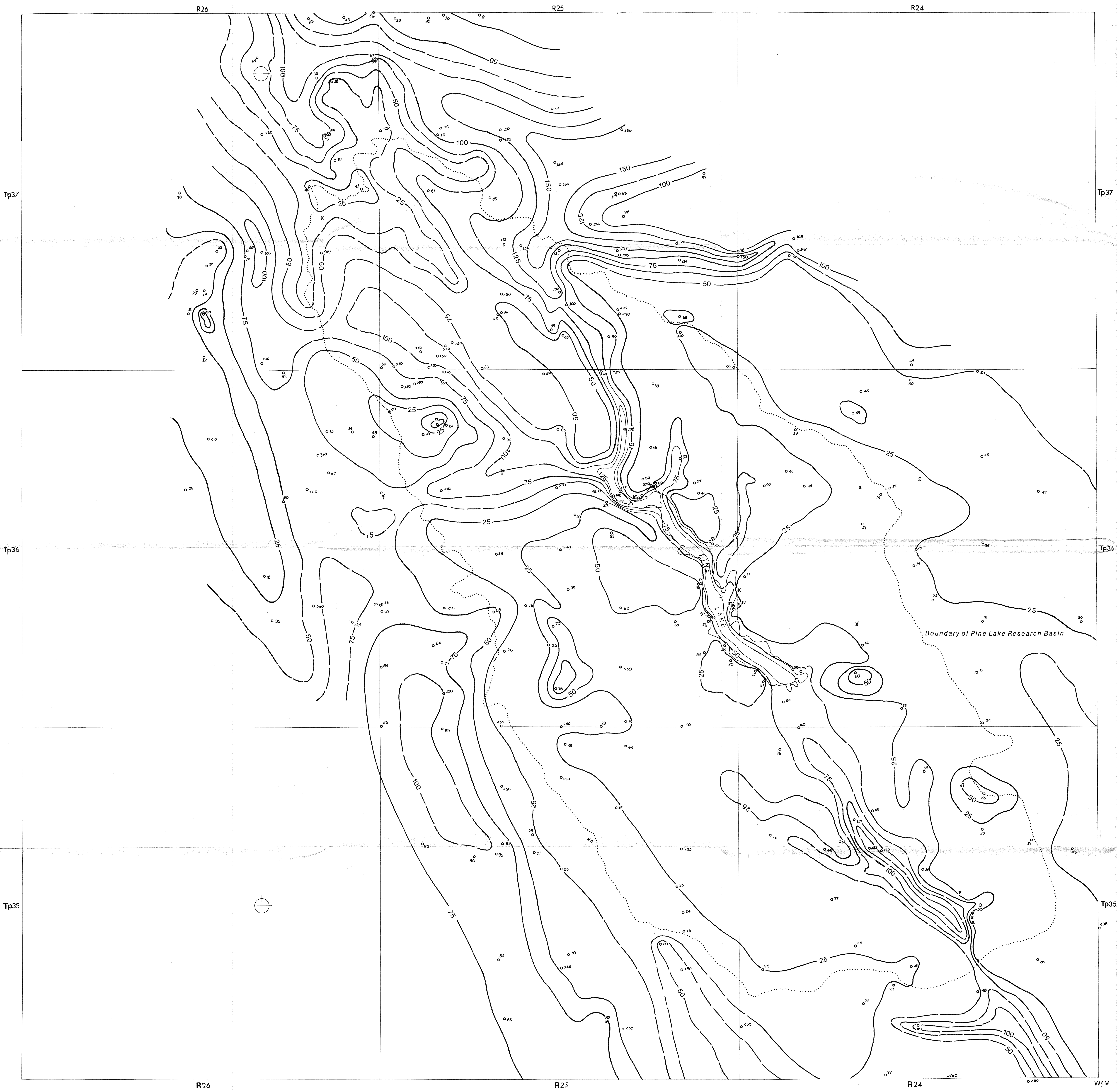


FIGURE 28

ISOPACH MAP OF THE GLACIAL DRIFT PINE LAKE RESEARCH BASIN

LEGEND

o Control Point

50 Contour Defined

25 Contour Assumed

x Bedrock Exposure

CONTOUR INTERVAL = 25 ft.

SCALE 1 : 50,000

1 0 1 2 3 miles

1 0 1 2 3 4 kilometres

Garven, G. (1980), M.S. Thesis, University of Arizona

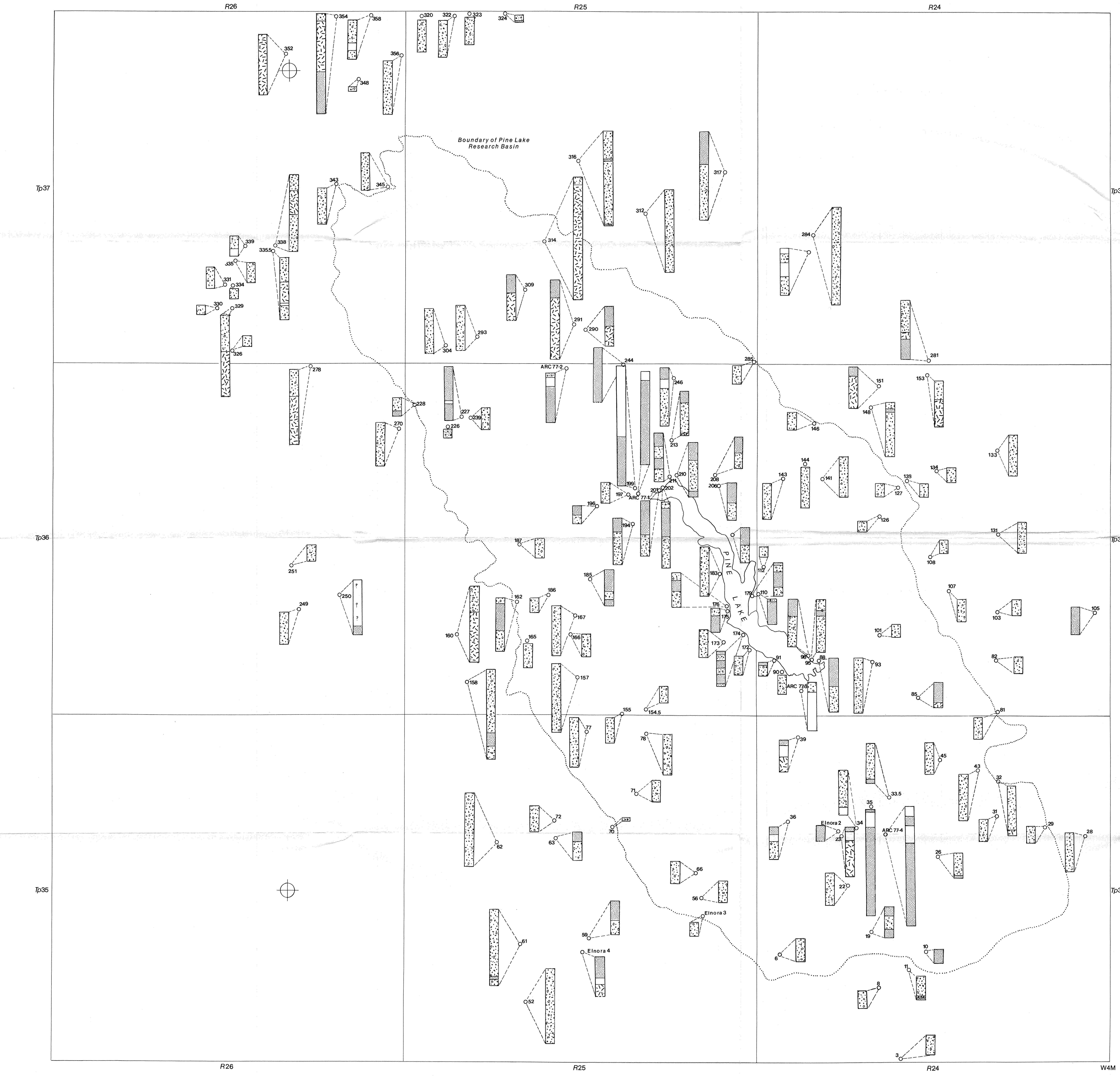


FIGURE 29

BOREHOLE GEOLOGY
PLEISTOCENE-RECENT DEPOSITS
PINE LAKE RESEARCH BASIN

LEGEND

GEOLOGY INFERRED FROM DRILLER'S LITHOLOGS;

☐	SILT (fluvial)
▨	SAND and GRAVEL (outwash; in places reworked by wind and of glaciolacustrine origin)
▨	GRAY TILL (usually yellow or brown in colour where oxidized; sandy clays are prominent)
▨	BLUE TILL (usually blue-gray, blue, or black clay-rich till)

36 CONTROL LOG and INDEX NUMBER

(see Appendix A for index number data)

0 10 20 30 40 50 (feet) VERTICAL SCALE OF LOGS
(1 cm = 10 feet)

SCALE 1 : 50,000

1 0 1 2 3 miles

1 0 1 2 3 4 kilometres

Garven, G. (1980), M.S. Thesis, University of Arizona

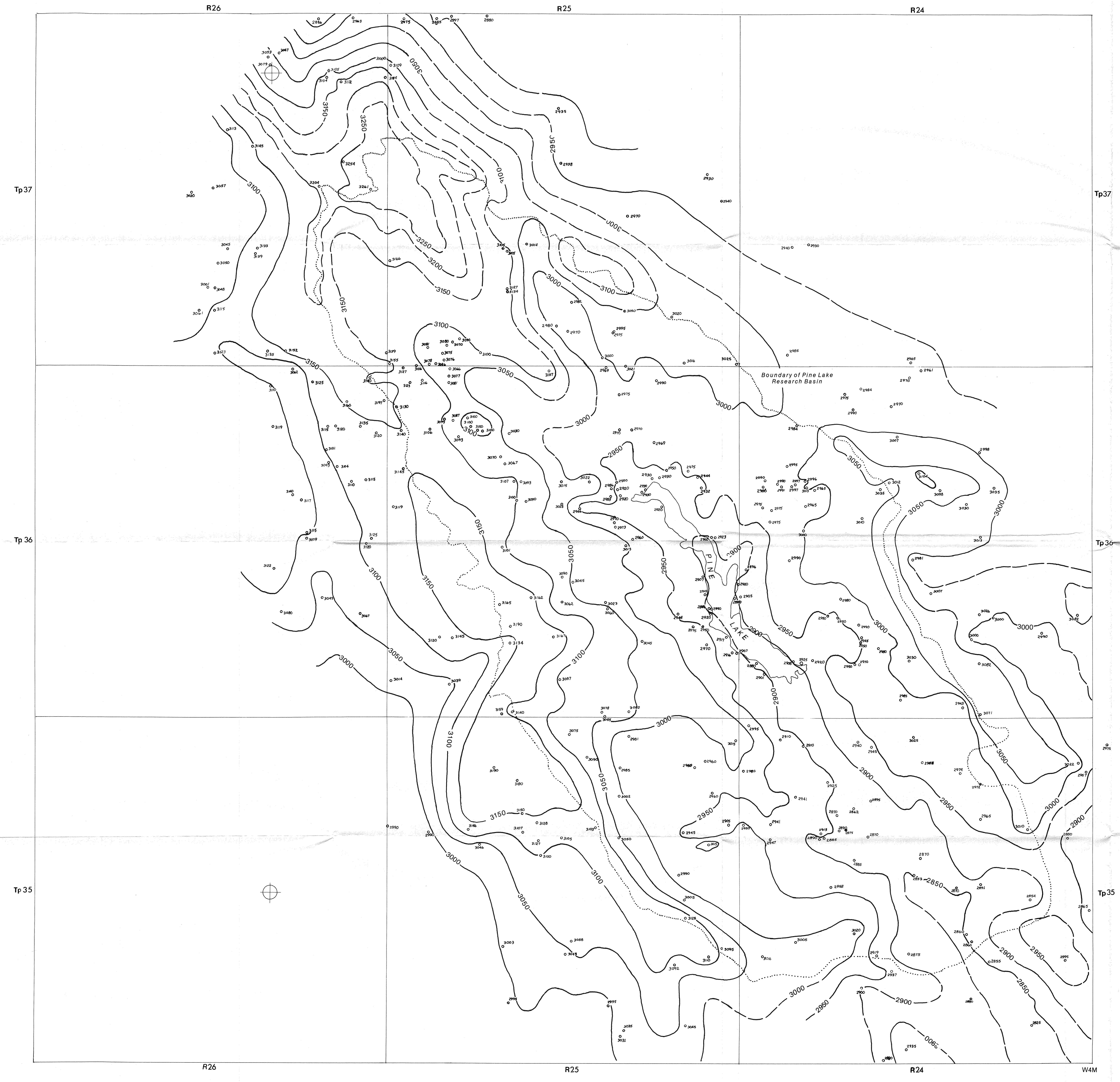


FIGURE 32

NON-PUMPING WATER LEVEL MAP PINE LAKE RESEARCH BASIN

Garven, G. (1980), M.S. Thesis, University of Arizona

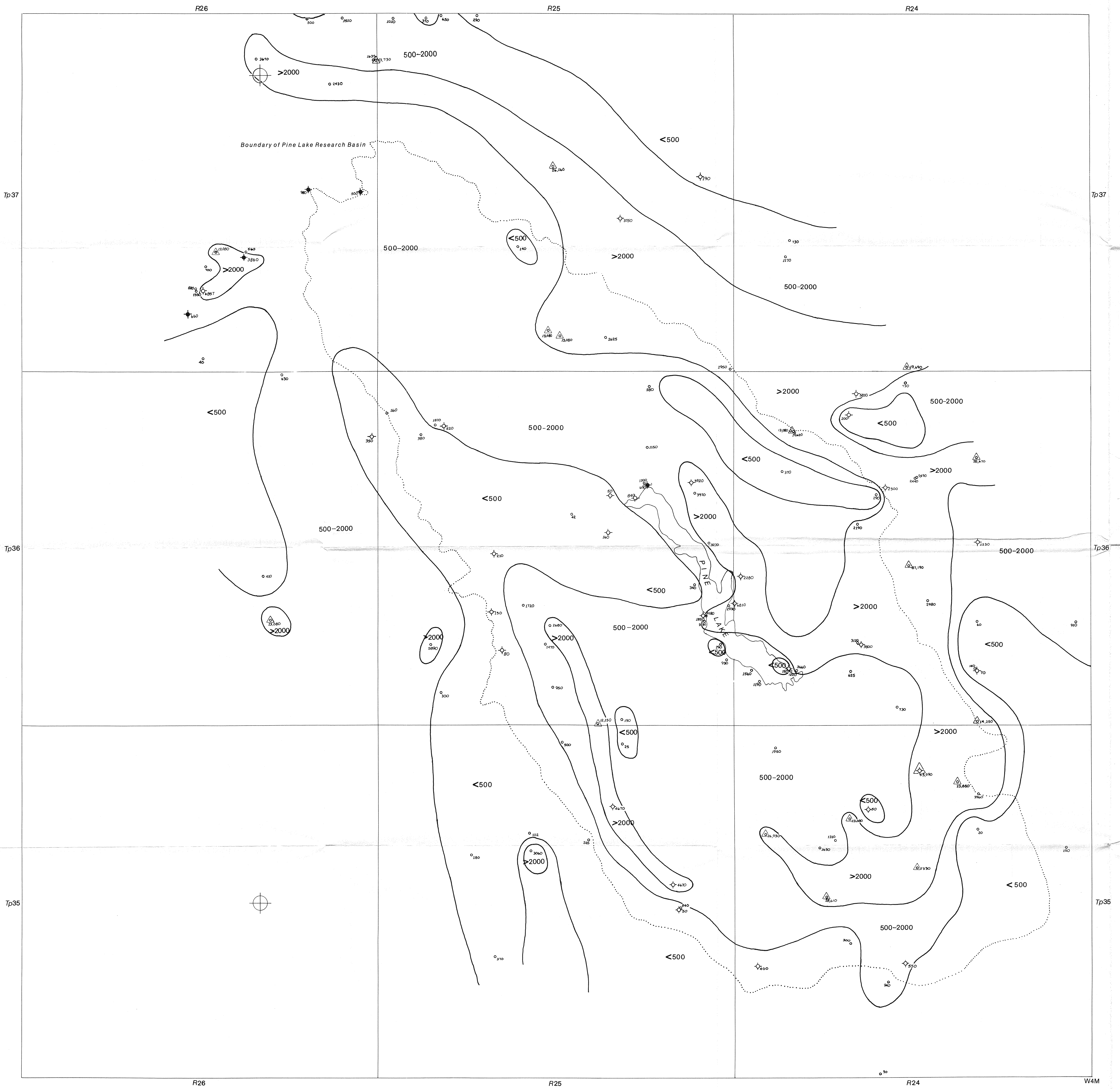


FIGURE 36

TRANSMISSIVITY MAP
PINE LAKE RESEARCH BASIN

LEGEND

(ALL TRANSMISSIVITY VALUES ARE EXPRESSED IN THE UNITS OF IGPD/FT)

- ✦ value derived from drawdown data-short pump test
- ⌖ value derived from recovery data - bail test
- ° value estimated from total drawdown reported (apparent transmissivity)
- △ anomalous value (due to negligible drawdown)

SCALE 1 : 50,000

1 0 1 2 3 miles

1 0 1 2 3 4 kilometres

Garven, G. (1980), M.S. Thesis, University of Arizona

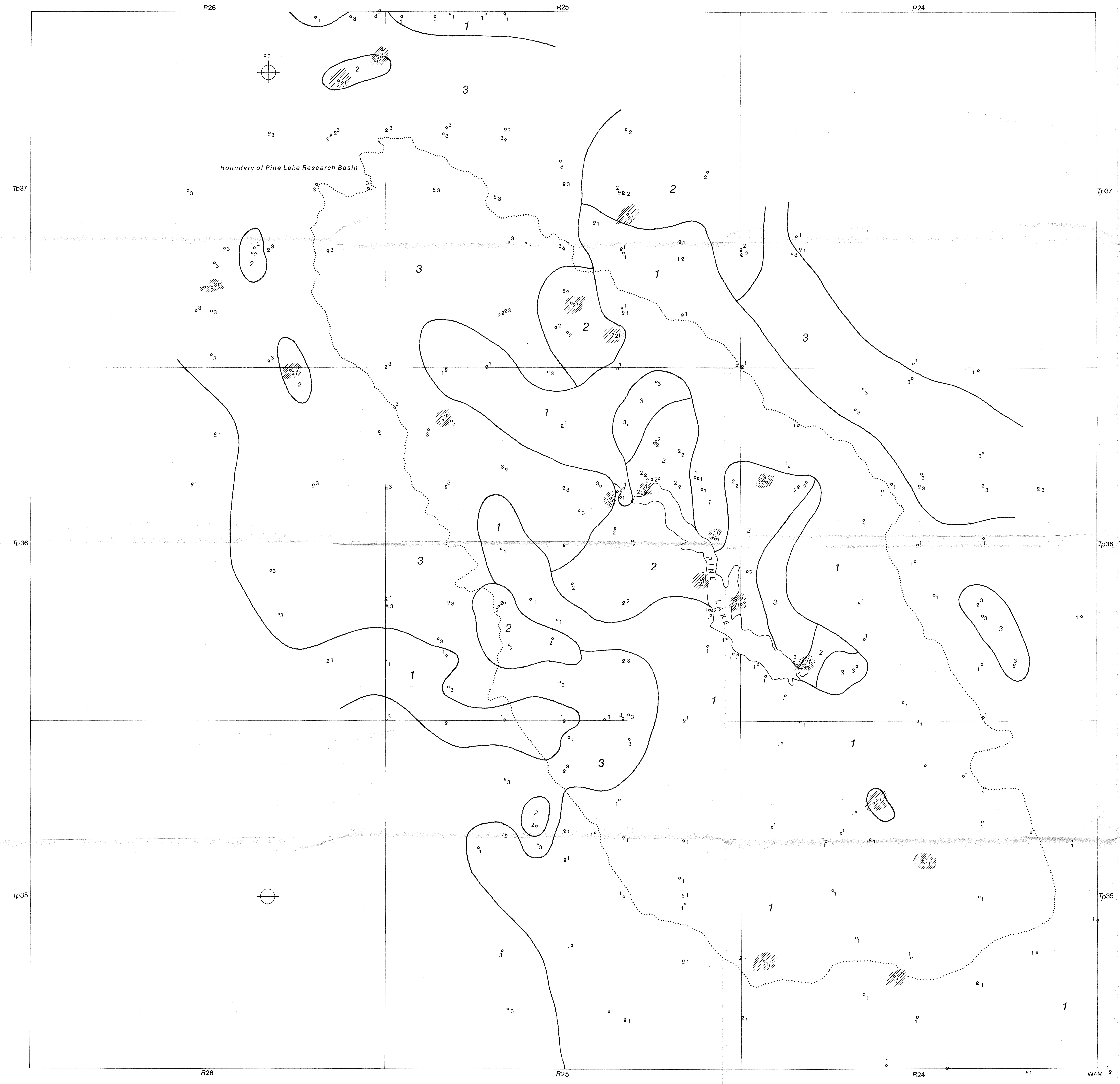


FIGURE 37

LITHOLOGY OF AQUIFERS IN THE SHALLOW BEDROCK (0-300 ft.) PINE LAKE RESEARCH BASIN

LEGEND

CONTROL POINT: -reported in water well log .... ∘
-interpreted from electric log .... ♀

1	Mainly Sandstone
2	Mainly Shale
3	Sandstone, Siltstone, and Shale
▨	Aquifer reported to be fractured

SCALE 1 : 50,000

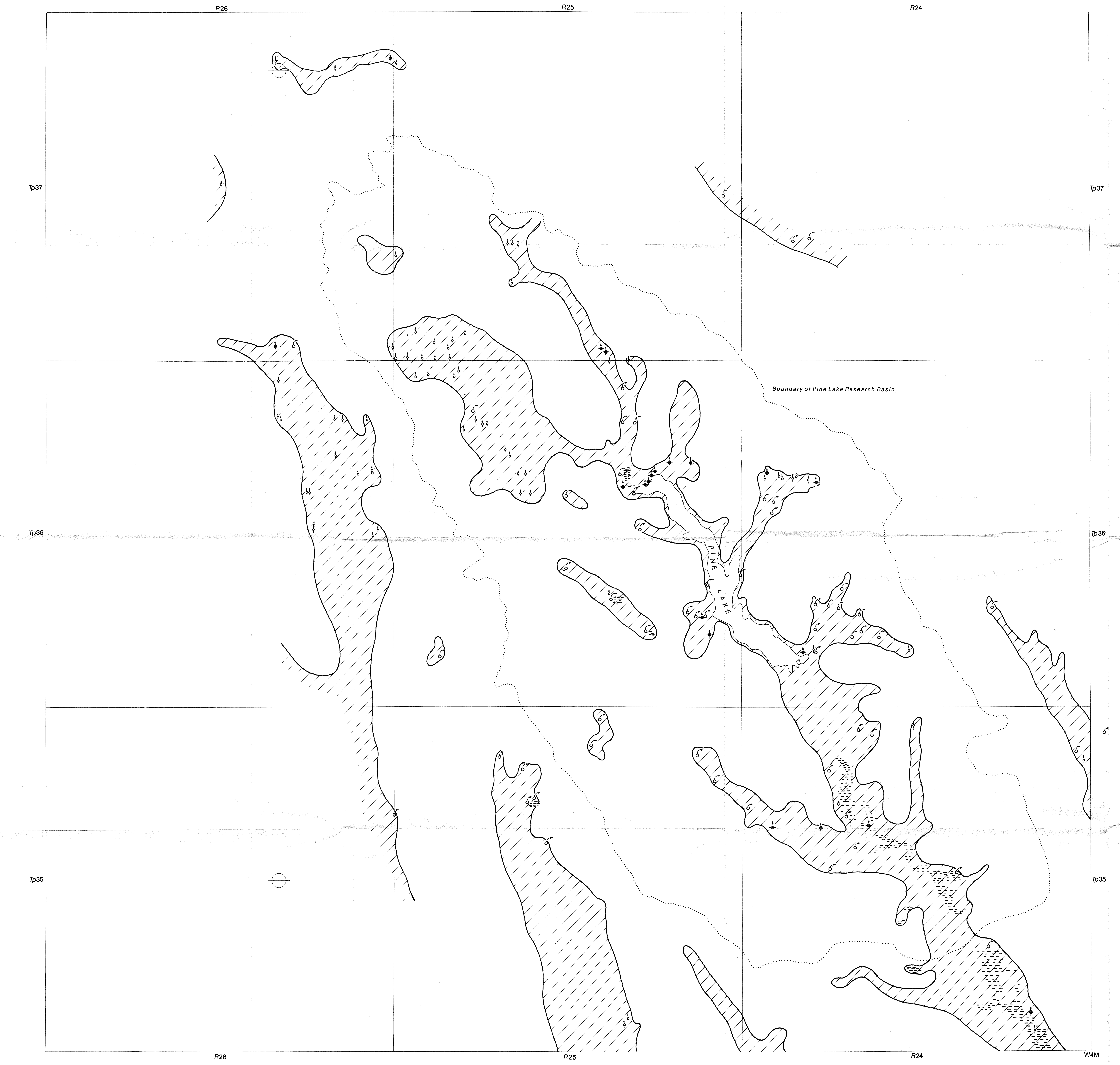
1 0 1 2 3 miles

1 0 1 2 3 4 kilometres

Garven, G. (1980), M.S. Thesis, University of Arizona

FIGURE 38

FIELD EVIDENCE OF GROUND-WATER DISCHARGE PINE LAKE RESEARCH BASIN



LEGEND

- ✦ Flowing well
- Flowing seismic shot hole reported
- Spring
- ▨ Discharge area
- Salt precipitates in soil

SCALE 1 : 50,000

Garven, G. (1980), M.S. Thesis, University of Arizona

FIGURE 39

HYDROGEOLOGICAL CROSS-SECTION

PINE LAKE RESEARCH BASIN

LEGEND

- ▨ DRIFT
- ▨ SANDSTONE
- ☐ SILTSTONE and SHALE
- | 2945 Water Well with Hydraulic Head Value (feet)
- → Direction of Groundwater Flow
- — 3050 — Head Equipotential (feet)
- ϭ Spring

Garven, G. (1980), M.S. Thesis, University of Arizona

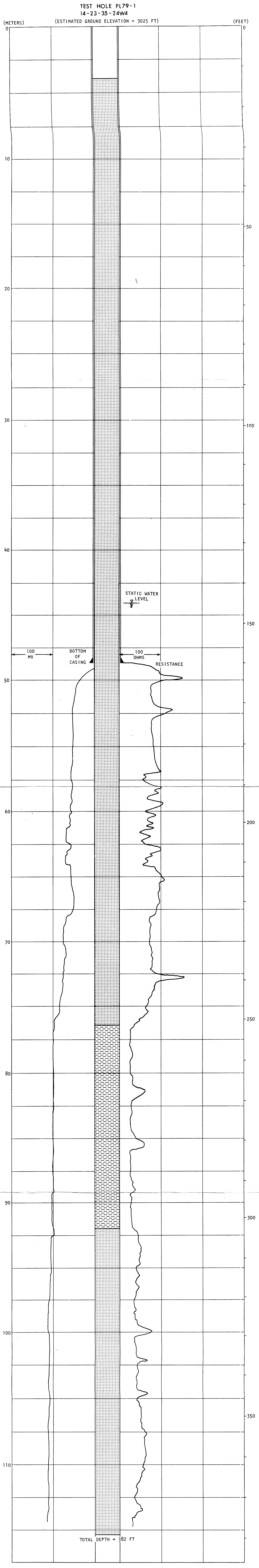
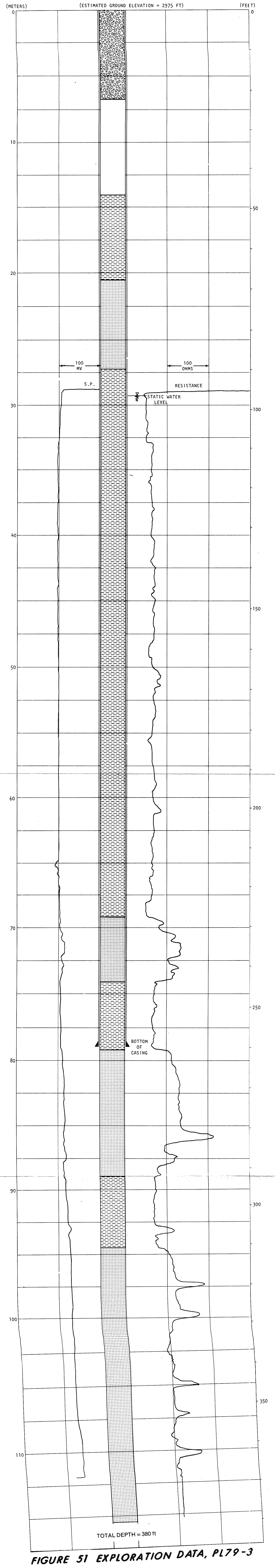


FIGURE 46 EXPLORATION DATA, PL 79-1

FIGURE 49 EXPLORATION DATA, PL 79-2



TEST HOLE PL79-3
4-26-36-25W4
(ESTIMATED GROUND ELEVATION = 2975 FT)

FIGURE 51 EXPLORATION DATA, PL79-3

FIGURE 53 EXPLORATION DATA, PL 79-4