Bulletin 35

CONTRIBUTIONS TO THE HYDROGEOLOGY OF ALBERTA

Groundwater Division

Alberta RESEARCH COUNCIL

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THE HYDROGEOLOGICAL RECONNAISSANCE MAPS OF ALBERTA

by J. Tóth

ABSTRACT

In 1968 a program of hydrogeological reconnaissance mapping of Alberta was started by the Alberta Research Council, with completion envisaged in approximately 11 years. The purpose of the program is to publish hydrogeological maps — graphic portrayals of the groundwater conditions and their controlling factors — for each of 47 different areas in the province. These maps will provide an overview of the hydrogeological conditions in the province, and as well will assist in the solution of groundwater-related problems such as water resources development, land use planning, civil engineering and environmental queries, basic and applied research, and the planning of future research projects. The maps are published at the scales of 1:125,000, 1:250,000 or 1:500,000 depending upon the amount of available data. The main items on a typical map sheet are a central main map, four hydrogeological cross sections, four to six side maps, a conversion table and a legend. The maps, though self-contained, are accompanied by short reports which give information on features not readily illustrated pictorially. The sources of basic data include water well drillers' reports, oil company information, geological reports, chemical analyses of water samples, field surveys, test drilling and pump testing. The maps are produced at a rate of one map sheet per geologist per year or a total of two to four map sheets annually. Out of the approximately 47 map areas of the province 32 have been mapped to date and maps for 15 areas have been published. The average cost of the completed maps to the Alberta Research Council is approximately \$15.50/sq mi (\$6.00/km^2) of area mapped.

INTRODUCTION

Since its establishment in 1955, the Groundwater Division of the Alberta Research Council has been called upon to perform three types of activities: counselling, surveying, and research. Survey activities have been given top priority in the division's programs since 1968 in order to develop a comprehensive knowledge of the province's groundwater conditions within the shortest possible time. This decision was based on the recognized need to:

1) enhance the effectiveness and efficiency of counselling by the division;
2) aid in the identification of research needed;
3) encourage and enable other agencies and professions to undertake groundwater-oriented work;
4) provide information needed by the rapidly expanding industry of the province.

In addition, a hydrogeological mapping project would provide an opportunity for training scientists entering a field relatively new in Canada.

Consequently, a hydrogeological reconnaissance mapping program was formulated and initiated by the author in 1968 with completion envisaged in approximately 11 years, that is by 1979.

Scope and present status of the mapping program

The objective of the program is a complete set of hydrogeological reconnaissance maps for Alberta. The province has an area of 255,000 sq mi (660,000 km^2) which has been divided into 47 mapping projects on the basis of the National Topographic System (NTS) (Fig. 1.1). These units vary in size from approximately 4,800 sq mi (12,400 km^2) in the north to 6,000 sq mi (15,550 km^2) in the south of Alberta. Typically, one geologist and one assistant are assigned one map unit of average population density (that is, average data density) or two sparsely settled map units per year.

Thus, most of the final maps will have a scale of 1:250,000 but some, because of the scarcity of data, will be at a scale of 1:500,000. On the other hand, the Edmonton area, which has a high density of data, has been mapped by four teams, and the four final maps will be published at a scale of 1:125,000.

The maps are designed to be self-contained but each one is accompanied by a short report which summarizes the general, typical, and anomalous conditions in the map area. Data that cannot be easily illustrated on the maps are also included in the reports.

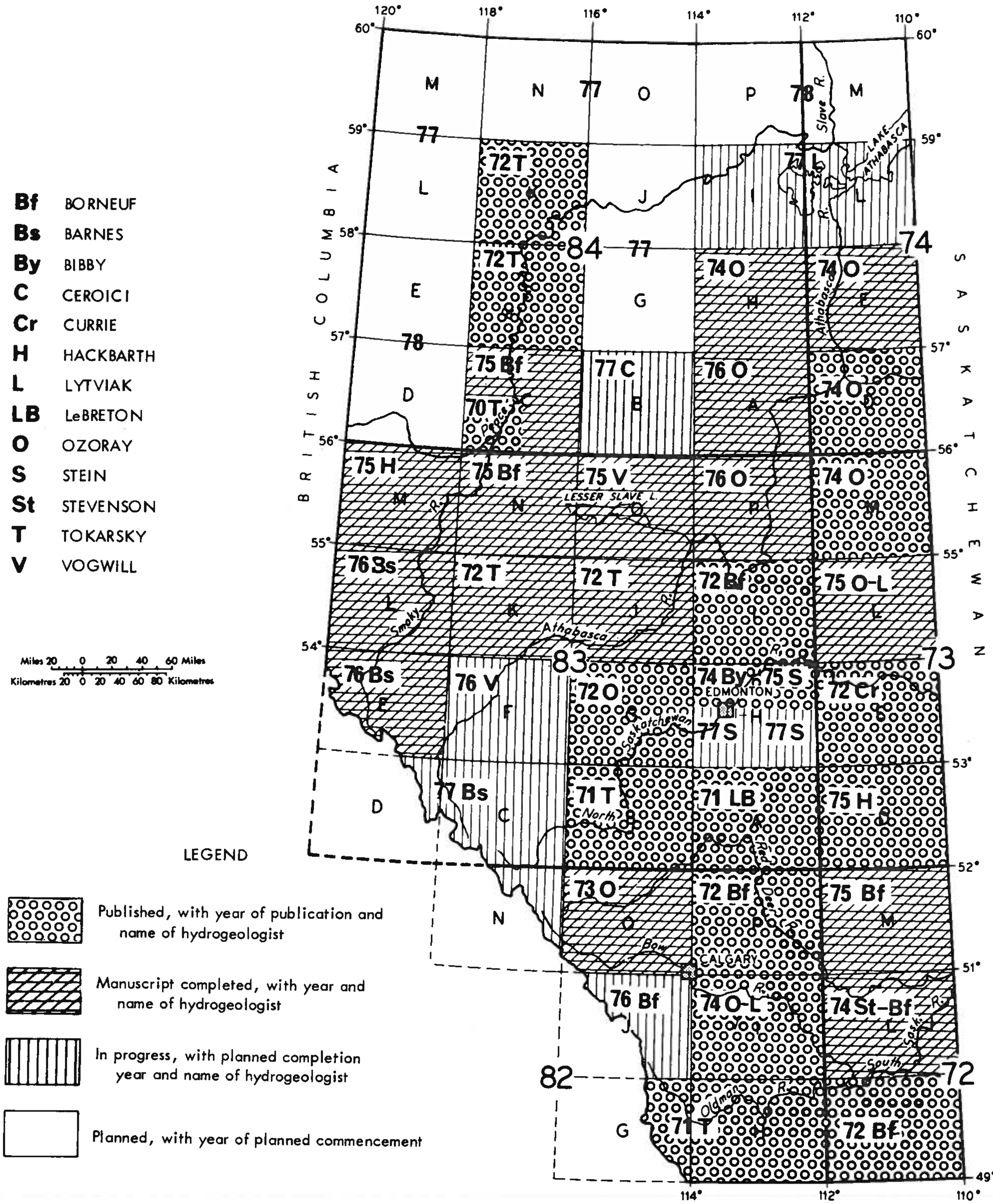

FIGURE 1.1 *Status of the hydrogeological reconnaissance mapping program of the Groundwater Division*

The maps are intended to provide information for various groups such as explorers looking for groundwater, environmentalists and managers planning land use and making inventory of groundwater sources, engineers attempting to solve design problems, and hydrogeologists performing basic and applied research.

Since the readership of the maps is diverse, an attempt is made to give a balanced portrayal of the hydrogeological environment and the groundwater regime and to not emphasize unduly any particular aspect of the groundwater conditions.

To date work has proceeded largely according to plans. In 1970 the pilot map on a scale of 1:125,000 was printed (Tokarsky, 1971). The following year the first hydrogeological map of a full mapping unit was published on a scale of 1:250,000 (Le Breton, 1971). On the basis of experience gained from these two maps, the initial provisional set of map symbols was revised and a standardized "Legend" was produced (Badry, 1972). To date work has been completed on 32 map units (approximately 172,800 sq mi or 447,500 km^2), and 16 hydrogeological maps have been published covering 15 map area units (approximately 60,000 sq mi or 155,000 km^2) as shown in figure 1.1.

The present program is expected to be completed in 1979. By that time hydrogeological reconnaissance maps will have been produced for all parts of Alberta and the emphasis in survey activities will likely have shifted into two other directions:

1) the production of a hydrogeological monograph or atlas for Alberta;
2) the preparation of large-scale, detailed hydrogeological maps for selected areas.

The monograph will represent a synthesis of the results of the present program complemented with new data, and the areas will be selected on the basis of scientific interest or economic potential.

PROCEDURE OF MAP PRODUCTION

The hydrogeological reconnaissance program comprises 47 mapping projects. The goal of each project is the publication of one Alberta Hydrogeological Map. This means that raw data must be transformed into simplified, publishable information. The process involved may be broken down into the following six steps:

1) collection, organization, and storage of basic data;
2) production of the "Alberta Hydrogeological Information Maps" on a scale of 1:50,000;
3) compilation of available information into a preliminary map (scale 1:250,000 or 1:125,000);
4) acquisition and generation of new information;
5) synthesis of information into map and report manuscripts;
6) editing, drafting, and printing.

Collection of existing data

The first step is carried out by an average of three full-time clerical employees of the division's data center under the direction of one geologist. In addition, temporary assistants occasionally supplement the data center's staff. Readily available raw data are collected from water well drillers, Alberta Environment public health services, consulting engineers, oil companies, and the division's own staff (Fig. 1.2), and include lithologic logs, pump test results, chemical analyses, field observations, hydrographs, water temperatures, and so on. Most of the data are processed manually, stored in folders, and filed by location, each folder representing one observation point or one investigation. Computerized storage of information is being introduced gradually, starting with chemical analyses, seismic shot hole data, and data from selected areas such as the northwest portion of the Edmonton area.

The "Alberta Hydrogeological Information Maps"

The next phase is the reduction of the data center's information into an "Alberta Hydrogeological Information Map": a graphical and numerical representation of readily available data on a scale of 1:50,000 (Fig. 1.3). This information is plotted according to the legend and symbols developed by the division (Badry, 1972). One reconnaissance map area unit contains 16 sheets of information maps (Figs. 1.1 and Plate 1.1) which are bound in one volume and form the starting point of any mapping project.

Preliminary hydrogeological reconnaissance map

The point-type, factual data of the information maps are then converted into preliminary interpretive maps on scales of 1:125,000 or 1:250,000 according to the mapper's preference. During this process a tentative picture is formed of the region's hydrogeological conditions and needed additional data are identified.

Acquisition of new data

New information is acquired by the mapping team in various ways including: rechecking of the data files of agencies mentioned previously; analysis of air photos and geological, pedological, meteorological, and hydrological reports; well survey; field mapping; collection of water samples; test drilling; performance of production tests and aerial reconnaissance by fixed wing light aircraft or helicopter or both. In populated areas major emphasis is placed on well surveys, drilling, and production tests, while mapping of field features and collection of water samples from springs and seeps are the chief mapping methods in the more remote regions. Generally in each map area, depending on local conditions, 4 to 20 testholes are drilled;

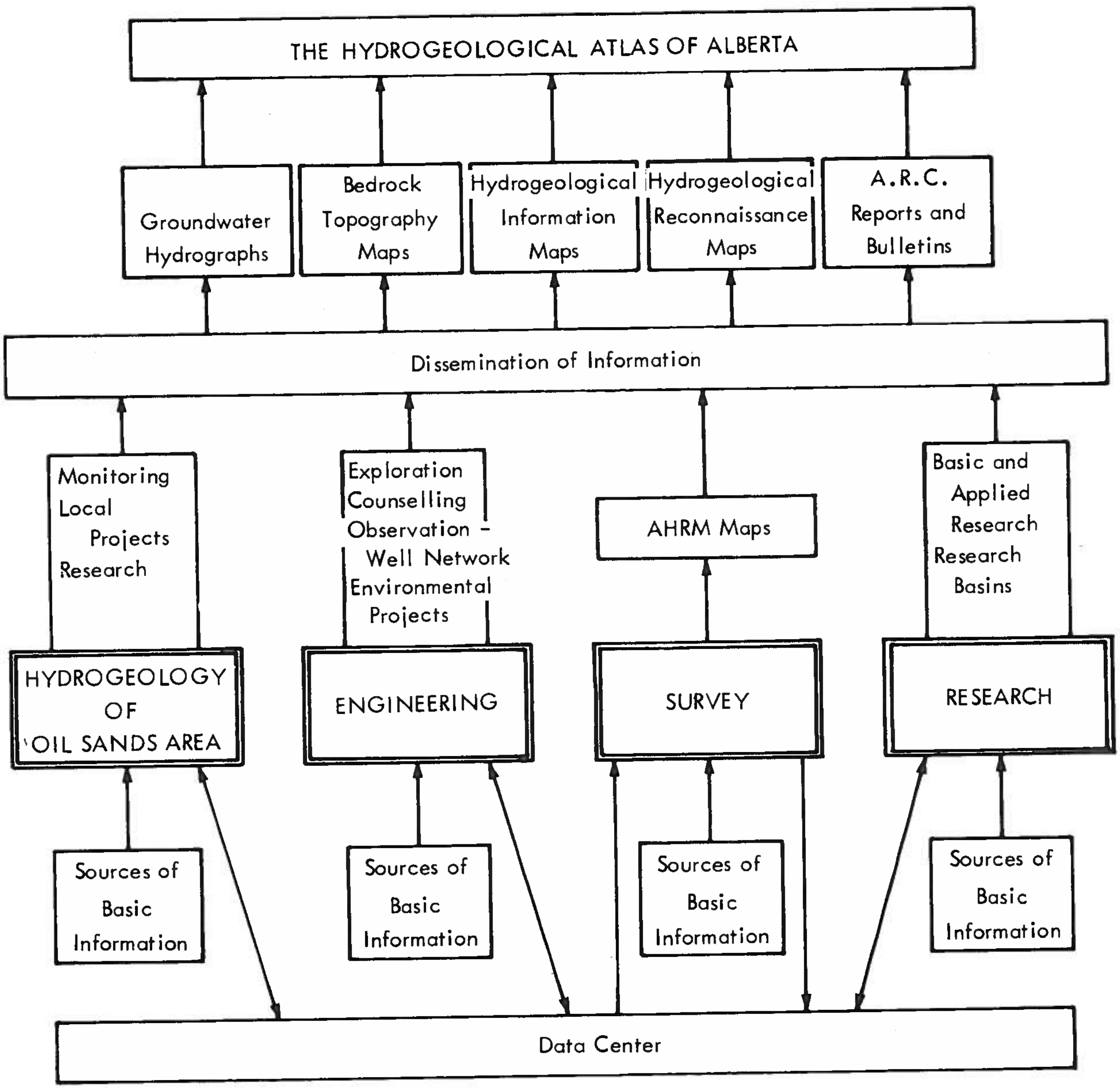

FIGURE 1.2 Diagrammatic summary of the structure and scope of work of the Groundwater Division

four or five major pump tests (that is, of several days' duration and with observation wells) and several tens of minor tests (2 hours duration and no observation wells) are conducted; 10 to 40 hours time is spent flying; 50 to 400 new water samples are collected and analyzed; and an average of 2 months is spent in field mapping. An attempt is made to drill the testholes in areas where the information derived from them may verify previous ideas or effect new discoveries.

Synthesis of data and the manuscript map

During this step in producing the map newly acquired information is incorporated into the preliminary map and a short auxiliary report is written. The results are presented on the map in such a manner as to portray the hydrogeological conditions of the mapped area as completely and explicitly as possible. No aspect of these conditions is deliberately accentuated for any purpose. The manuscript map sets out the information on several overlays separated according to the colors that will appear on the final printed map. The accompanying report, usually 15 to 20 pages long, summarizes the general conditions, underscores the typical and anomalous features, and outlines information that may be pertinent but is not shown on the map.

Editing, drafting and printing

This last phase includes scientific and cartographic editing, drafting, and printing. Editing for the scientific content of the maps and reports is performed on the manuscripts within the Groundwater Division. Each project undergoes repeated and informal reviews by staff members during the preparatory stages. The maps and reports are then presented for criticism to the division's staff, and are formally edited by two staff members.

Subsequently, the manuscripts are edited by the editorial staff of the Earth Sciences Branch for accuracy, consistency of symbols used, and for compatibility with drafting and printing requirements. After necessary corrections, the manuscripts are passed on to Drafting Services or outside drafting companies. Line work is done in black ink or, more recently, by a technique called scribing. Etched peel coats are used to produce the boundaries of areas of color. Then a separate photographic negative is prepared for each of the eight different colors that will be used in printing the final map. From these, eight printing plates are produced, again one for each color, and the map is then printed, using the offset technique. Due to the scarcity of sufficiently large presses, printing has, to date, been done in Winnipeg or Vancouver.

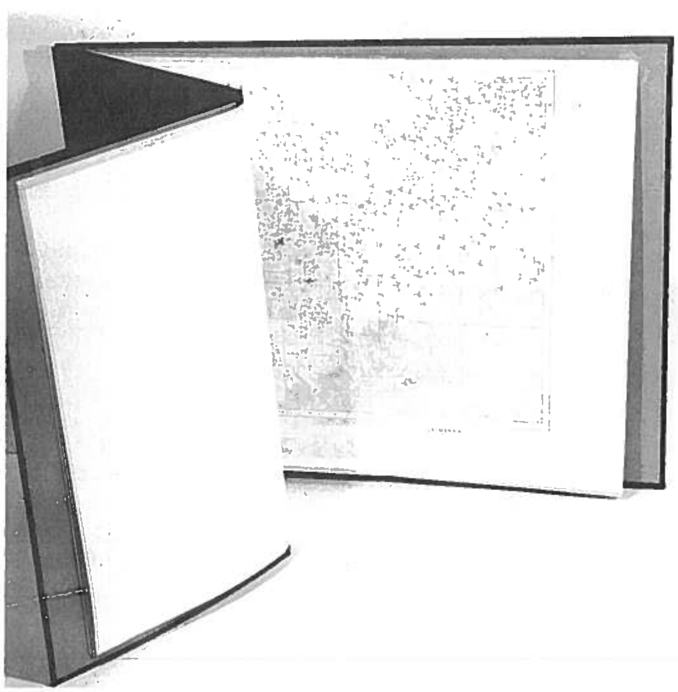

PLATE 1.1 Sample atlas of Alberta Hydrogeological Information Maps

These briefly outlined technical procedures and their sequence appear relatively simple but it has taken over 4 years and a large amount of experimentation by trial and error to develop an adequate production system and further evolution is anticipated.

Costs

The approximate cost to the Alberta Research Council to produce an average hydrogeological map may be broken down approximately as follows:

Salaries	\$25,000 - \$30,000
Operation (drilling, fieldwork, etc.)	30,000
Services (drafting, editing, chem. analyses, etc.)	10,000
Printing (1,500 copies)	6,000
Overhead (10%)	7,000
	\$83,000

or approximately \$15.50 per square mile (\$6.00/km^2).The approximate cost of the entire program (47 map area units) will be \$4,000,000 in 10 to 11 years.

DESCRIPTION OF THE ALBERTA HYDROGEOLOGICAL RECONNAISSANCE MAPS

Scale, intended uses and prototype

As indicated previously, the basic scale of the mapping is 1:250,000 even though other scales may be used where necessary. The scale of 1:250,000 seems to satisfy both the demand for sufficient detail to show local conditions, and the demand for sufficient generalization to obtain a province-wide overview. That is, the greatest general usefulness is obtained with a minimization of the time, costs, and personnel required for the program's completion. In addition, the availability of a complete set of NTS maps has been an argument in favor of this scale.

As an example of the contents, method of presentation, and potential uses of the maps, the prototype of the series, namely the Grimshaw-Chinook Valley Hydrogeological Map (Tokarsky, 1971), is presented here (in pocket), but in two colors rather than the normal eight. Although this map may differ in certain aspects from subsequent maps in the series, such as the size of area covered, scale and some symbols used, its essential features have been retained in all later maps.

Owing to the diversity of intended potential uses of the maps, the presentation of the hydrogeological conditions is attempted in terms of basic parameters. Thus the majority of the information is shown as components of the groundwater regime and of the hydrogeological environment rather than in terms of specific uses (domestic, industrial, and so forth). Expressions such as *potable, suitable, poor, good, adequate* and so on are avoided. The information sought by a map user will normally have to be composed from the data found in the maps. The user himself is thus expected to be familiar with hydrogeological concepts and practice, so it is likely that the majority of users will be consultants, engineers, geologists, and educated water well drillers.

Contents of the maps

An "Alberta Hydrogeological Map" typically consists of a centrally positioned main map, surrounded by four hydrogeological cross sections, several side maps, a conversion table, an index map, and the legend. In view of the anticipated potential uses the following items are shown on the maps:

1) areally extensive natural hydrogeologic conditions, such as: topographic relief, precipitation, stratigraphy of rocks, lithology of principal aquifers, hydrostratigraphy, drainage divides of surface water and groundwater, yield characteristics of rocks, nonpumping water levels, direction of groundwater movement, areas of flowing wells, chemical constituents in groundwater, and areas of saline soils;

2) natural hydrogeologic conditions that are local in character or are known only locally, and also those which are or appear to be anomalous, for example: annual evaporation, streamflow data, springs, seeps, isolated flowing wells, unusually high well yields in generally poorly producing areas and vice versa, water level fluctuations in observation wells, uncommon chemical characteristics, abnormal water temperatures, landslides attributed to groundwater, and so on;

3) artificially induced features including: hydraulic head depressions, artificial groundwater mounds, and the intensity and areal extent of groundwater contamination;

4) man-made installations such as: major production wells, infiltration galleries, spring catchments, observation wells, hydrometric stations, water pipelines, and so on.

A complete list of items that may occur in the hydrogeological maps is given with definitions and symbols by Badry (1972). This legend, compiled and adapted for Alberta conditions by the Groundwater Division, is based on *A Legend for Hydrogeological Maps* (IASH, 1962), the standard symbols used in Alberta on geological maps, and symbols adopted during the International Hydrologic Decade.

The main map contains information on movement, yield and conditions of occurrence of groundwater and groundwater-oriented installations. Around the main map are four cross sections showing hydrogeological conditions to the depth of investigation. The horizontal scale of the cross sections is the same as that of the main map thus enabling direct cross correlation. Situated outside the main

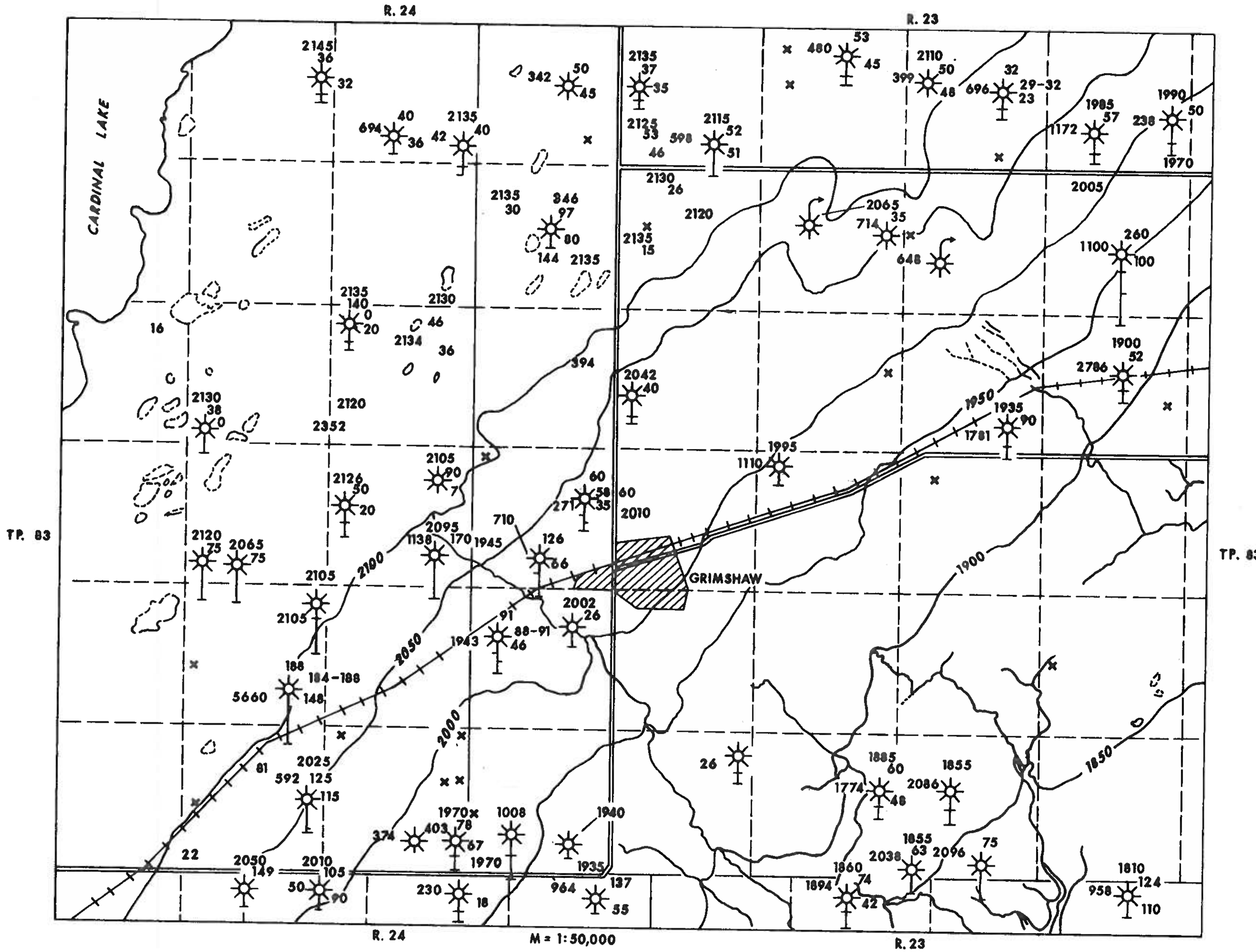

FIGURE 1.3 Sample section of a Hydrogeological Information Map

map-cross section complex are various side maps on a scale of 1:1,000,000 which show meteorology, bedrock geology, groundwater chemistry, data density, and optionally selected miscellaneous items such as the concentration of a chemical component or the depth of wells in the area. Any extra data or explanations are outlined in the accompanying report.

USES OF THE ALBERTA HYDROGEOLOGICAL RECONNAISSANCE MAPS

General remarks

In general, the Alberta hydrogeological maps can be used:
1) in the solution of groundwater-related practical problems;
2) in the identification of relevant research;
3) as an inventory of information; and
4) as the start of a comprehensive treatise on the hydrogeology in Alberta.

Among the uses mentioned above, the first is undoubtedly the most varied in scope and the most widely appreciated, if only because it satisfies current needs. Uses 2, 3 and 4 are, in fact, preparations for future studies and as such are of interest only to research groups and to the Groundwater Division itself. However, the author would like to underline the importance of these latter uses for dealing with practical problems. By an early evaluation of the hydrogeological conditions of an area, potential problems can be recognized and averted instead of having to be corrected after the fact.

Information from the hydrogeological maps can be obtained both directly from and by synthesis of the data presented. For example, the answer to the question of "where can an industrial establishment develop a 500 gpm (38 l/sec) supply within a specified area" can be read off directly from the yield colors on the map. However, to answer the question of where and how the same plant can dispose of its waste waters, synthesis of given data is necessary. The first method requires only a general knowledge of map reading while the latter demands hydrogeological expertise.

Examples

The diversity of possible application of these maps to the solution of groundwater-related problems is very great. However, a few typical cases should be sufficient for the purposes of illustration considering that all cases belong to one of two basic situations:

1) evaluation of the hydrogeologic conditions at a given site is required or,
2) sites with specified hydrogeologic conditions must be located.

The term "hydrogeologic conditions" is used here in its broadest sense and encompasses all components of the hydrogeologic environment and groundwater regime including: type of relief and magnitude of slopes; density and pattern of drainage systems; lithology and structure of the rocks; amount, types, and distribution of precipitation and evaporation; distribution of streams, lakes, and wetlands; yield characteristics of rocks; occurrence, quality, flow, and outcrops of groundwater; and so on.

Type situation 1: Site is given — hydrogeologic conditions to be evaluated

What are the hydrogeologic characteristics of the area located immediately south and west of Cardinal Lake and marked "K" on the map?

First, the information that is *explicitly* shown on the map for the area in question may be summarized as follows:

The area is flat to gently undulating and has a uniform southeasterly slope of approximately 12 ft/mi. The mean annual precipitation is between 16 and 17 in, approximately 60 percent of which falls in the form of rain. The rate of potential evapotranspiration exceeds that of the rainfall by several inches during the 5 summer months of heaviest precipitation.

The surface geologic material is a sand and gravel layer up to 120 ft in thickness overlain by other thin surficial deposits. It is underlain by 10 to 40 ft of Kaskapau shale which rests on 400 ft of sandstones, siltstones and shales of the Cretaceous Dunvegan Formation.

The gravels are partially saturated. The water table is generally low with depths of up to 60 ft below the land surface (cross section A-A' and well symbols). The depth to the water table decreases towards the lake. Generally, groundwater moves downward (indicated at observation well and by crosses on the water level contours), and laterally to the east at a low regional gradient of approximately 2 to 3 ft/mi. The annual range of water level fluctuations is approximately 0.5 ft as indicated by records obtained with an automatic water level recorder.

Along the northern boundary of the area considered (Secs 25-30, Tp 83, R 25, W 5th Mer) water moves northward and discharges onto the surface from a thin layer of gravels which is under partially confined conditions caused by unconsolidated drift occurring along the boundary line between Tps 83 and 84 on the west side of Cardinal Lake.

Possible well yields are highest and in excess of 500 igpm in the approximately 32 sq mi central portion of the area covered by the gravels and gradually decrease radially outward. Outside of the main area of the gravels the indicated yields are dominated by those in the Dunvegan Formation and are reduced to approximately 25-100 igpm.

Total dissolved solids are generally around 500 ppm. The chemical character of the groundwaters near the main intake areas (Secs 1-12, Tp 83, R 25, W 5th Mer.) is calcium-magnesium sulfate with up to 50 percent bicarbonate (hydrochemical side map, and cross section A-A', respectively). However, in the region just to the northwest of the lake, total dissolved solids increase up to the 2000 ppm range, the relative amount of sulfate increases to amounts in excess of 90 percent at the expense of bicarbonate, and sodium ion appears in amounts up to 25 percent.

The main information contained *implicitly* by the map for the area in question is the high permeability of the gravels as suggested by the lithology, by high well yields, and by low regional hydraulic gradients. The low mineralization of the water indicates either that little soluble matter is in the rocks or that groundwater movement is intensive, or both. The low water table in the highly permeable material probably reflects the fact that evapotranspiration exceeds precipitation during the summer months. It is also likely that the main water body of the gravels constitutes a recharge area while the marshy depression due west of the lake is an area of groundwater discharge.

Different hydrogeologic conditions are found only about 6 to 10 mi south of the area discussed above, that is in the general region of the boundary between Tp 81 and 82 in R 25. Here the land surface is undulating and slopes evenly toward the deeply incised valley of the Peace River at a rate of approximately 60 to 80 ft/mi. The annual precipitation is around 15 in. The deposits of the area consist of more than 800 ft of thickly bedded Quaternary clays, silts, sands, and gravels of glacial, lacustrine, and fluviatile origin. This sequence fills a deeply incised channel on the surface of the bedrock which consists of beds of Cretaceous sandstones and shales.

There is a strong surfaceward component of the groundwater flow as indicated by numerous flowing wells, an artesian area and a large (135 igpm) spring. The water table is near the land surface although it is drawn down considerably near the edge of the steep river valley.

Generally the yields to wells from the argillaceous Quaternary beds are low. Rates of 5 to 25 igpm may be obtained from sand and gravel pockets of the near-surface till (Qt on cross section A-A'), while only 1 igpm from the lacustrine clays below it (Qc); 1 to 25 igpm may be developed from silts, sands, and gravels in the lowermost unit of the unconsolidated deposits. The bedrock shales yield 1 igpm.

The quality of groundwater changes rapidly southward from 500 ppm total dissolved solids to 2000 ppm, with an associated facies change from (CaMg) (HCO_3^-,$SO_4^=$) to mainly (Na, CaMg)$SO_4^=$. The increase in the mineralization of the water is in the same general direction as that of the water movement. Saline soils are present at various locations.

Implied in the map's information are: generally low permeabilities, sluggish movement of groundwater and discharge conditions. Landslides, slumping, frost heaving, and marshy conditions could be expected as a result of the combined effects of the high clay content, shallow water table, and surfaceward movement of groundwater.

Type situation 2: Conditions specified — area to be found

The second type of map use is the location of areas with specified hydrogeological conditions. This is illustrated here by the hypothetical example of a plant that needs a site for the treatment and disposal of large amounts of acidic liquid waste anywhere in Tps 81-83 and Rs 25-26, W 5th Mer, southwest of Cardinal Lake. The treatment and disposal facilities must be such that effluents do not enter the groundwater regime, that a major natural drainageway is nearby, and that potential water resources of the region are safe against accidents.

The hydrogeologic makeup favoring the above requirements include: low permeability of near-surface formations, ascending movement of groundwater and proximity of a major river.

From the point of view of these constraints the site most suitable for the waste disposal facilities appears to be in the area in Secs 12-13, Tp 82, R 26, W 5th Mer and Secs 7 and 18, Tp 82, R 25, W 5th Mer (discussed above) for the following reasons:

1) The rocks in the area are poorly permeable, and are thus poor conduits for contaminating effluents. This is indicated by the presence of argillaceous sediments (Qt and Ql), and by low well yields (areas marked "F").

2) The area is a region of groundwater discharge, so a "hydraulic perch" will keep the liquid wastes near the land surface and prevent groundwater contamination. This condition is indicated on the map by flowing wells, an artesian area, rise in water levels with increasing well depths ("beaded" piezometric contours), salt precipitates and a relatively high degree of mineralization of the groundwater.

   In addition, no valuable water resources are endangered now or in the future because the well yields are low (5-25 igpm on cross section) and water quality is poor (TDS 2000 ppm, Fe 1-10 ppm, Na_2SO_4 60%). A permanent creek may provide access to the Peace River for the treated effluent, while the lake in Sec. 21 might be considered for the plant's water supply.

By contrast, the least suitable site for the waste water disposal system should be the region immediately south and west of Cardinal Lake marked "K" on the map, because:

1) The area is a region of groundwater recharge so there would be a tendency for the wastes to descend from the water table toward the interior regions of the saturated

zone. This condition is shown by crosses on the water level contours indicating declining hydraulic heads (observation well) with increasing well depth (crosses on contours).

2) The rocks are highly permeable and so are good conductors for contaminants. This is inferred from the presence of thick gravels and high (>500 igpm) well yields.
3) Valuable water supplies might be endangered by contaminants. The good resource potential of the area is indicated by the good well yields and by good water quality (TDS<1000 ppm, major constituents Ca, Mg, SO_4 and HCO_3 and little Na^+ and Cl^-).

Miscellaneous examples

The potential for varied uses of the hydrogeological maps is illustrated by some further hypothetical examples:

1) *Regional planning decisions:* As a result of the government's decentralization policy a major research facility and associated urban development is planned for either Chinook Valley or Smithmill. Which site is preferable from the point of view of groundwater conditions?

   Smithmill appears to be preferable as adverse conditions associated with groundwater discharge are more intensive at Chinook Valley. These conditions are: flowing wells, saline soils and probable marshy grounds, high (3000 to 4000 ppm) mineralization, and unfavorable type (Na_2SO_4) of the potential water supplies. Water quality is somewhat better [$CaMg(Na)HCO_3(SO_4)$; 1000 to 2000 ppm], and expected problems with shallow water tables and concrete corrosion (because of SO_4 in soil water) are less likely at Smithmill.

2) *Technical planning:* Which routing is preferable hydrogeologically for a highway between Warrensville Centre (Sec 30, Tp 84, R 23) and Craven Lake (Sec 32, Tp 85, R 23): (a) the present Highway No. 35, or (b) one approximately 2 miles to the east?

   It appears from the map that alternative (b) is preferable because the descending direction of groundwater, the deeper water table, and the presence of coarse sands and gravels (that is, well drained soils thus generally dry conditions) along the water divide would cause less problems for construction and maintenance of the road bed and pavement than would the occurrence of marshy conditions, ice lensing and sulfate waters found generally in discharge areas.

3) *Detection of sources of contaminants:* Gasoline appears in Grimshaw's water supply. The areal distribution of gas stations is uniform around the town within a radius of 5 miles. What would be the reasoning based on the hydrogeological map in planning an investigation to locate the source and to remedy the situation?

   The town obtains its water supply through a pipeline from a spring situated approximately 2 miles to the north. The spring is fed from the northwest through the gravels, probably from Cardinal Lake. The most likely source of contamination must, therefore, occur in this direction, rather than to the south and east where artesian conditions minimize the likelihood of groundwater contamination from shallow sources. An investigation to locate the source of gasoline should thus be concentrated in the area north and west of the spring used as the town's water source.

Present usage

It often takes time for an innovation to gain acceptance. This is particularly true for such relatively abstract and technically complex products as hydrogeological maps. Yet, as the existence and availability of the Alberta maps is beginning to be known, their use is becoming increasingly more widespread and regular. For example, the maps are used by the Energy Resources Conservation Board in determining surface casing requirements for oil wells; by consultants and regional planning commissions to determine allowable well spacing in acreage development; by oil companies in location and evaluation of the potentials of water source wells; by consultants and government agencies for the evaluation of the hydrologic conditions in studies concerning power plant sites (for example, Dodds), lake level stabilization (Cooking Lake), fish hatcheries (Type 2 problem), and so on. In anticipation of future needs for the hydrogeological maps accelerated work has been requested by forestry agencies on some Foothills map sheets, by Planning Commissions in particular areas, and by industry in the Athabasca Oil Sands area.

Nevertheless, the maps are far from being fully utilized. Probable reasons for this situation may be the general lack of public awareness due to the newness of the maps and the limited number of problems areally coincident with published maps. Also, situations where they have been used may not have been reported to the author since many of the regular and major users are competent professionals (consultants, government engineers, and well drillers) not requiring assistance. In order to introduce the maps to specialists the division held four 2-day technical workshop seminars in 1973 and 1974 on their preparation and use. Total attendance exceeded 100.

In addition, the Groundwater Division not only prepares the maps but is also one of the principal users, and use will increase further once the series is complete. At present, the main uses of the maps by the division are in its technical advisory services and in the identification of gaps and deficiencies in available information. In counselling, most of the needed information can commonly be obtained from the maps; if not, the type and amount of new data required is made evident. Perhaps the most important type of use is the guiding of prospective groundwater developers to areas that are potentially best suited to their needs with respect to both quality and quantity. These users include land developers (acreages, subdivisions) and industry (packing plants, refineries, water for secondary recovery and so on).

The previously mentioned but by no means least important future use of the series will be as the starting point in the preparation of a comprehensive study of Alberta's hydrogeology, to be summarized in the "Hydrogeological Atlas of Alberta."

ACKNOWLEDGMENTS

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REFERENCES AND LIST OF HYDROGEOLOGICAL RECONNAISSANCE MAPS PUBLISHED OR COMPLETED BY JULY 31, 1976

Badry, A. (1972): A legend and guide for the preparation and use of the Alberta hydrogeological information and reconnaissance map series; Res. Coun. Alberta Rept. 72-12, 96 pages.

Barnes, R. (in prep.): Hydrogeology of the Wapiti-Mount Robson area, Alberta.

Bibby, R. (1974): Hydrogeology of the Edmonton area (northwest segment), Alberta; Alberta Res. Rept. 74-10, 10 pages.

Borneuf, D. (1972): Hydrogeology of the Drumheller area, Alberta; Res. Coun. Alberta Rept. 72-1, 15 pages.

Borneuf, D. (1972): Hydrogeology of the Tawatinaw area, Alberta; Res. Coun. Alberta Rept. 72-11, 12 pages.

Borneuf, D. (1976): Hydrogeology of the Foremost area, Alberta; Alberta Res. Coun. Rept. 74-4, 26 pages.

Borneuf, D. (in prep.): Hydrogeology of the Oyen area, Alberta.

Borneuf, D. (in prep.): Hydrogeology of the Peace River area, Alberta.

Borneuf, D. (in prep.): Hydrogeology of the Winagami area, Alberta.

Borneuf, D. (in prep.): Hydrogeology of the Kananaskis Lakes area, Alberta.

Currie, D. V. and N. Zacharko (1976): Hydrogeology of the Vermilion area, Alberta; Alberta Res. Coun. Rept. 75-5, 15 pages.

Hackbarth, D. A. (1975): Hydrogeology of the Wainwright area, Alberta; Alberta Res. Coun. Rept. 76-4, 17 pages.

Hackbarth, D. A. (in prep.): Hydrogeology of the Grande Prairie area, Alberta. Alberta Res. Coun. Rept. 76-4, 17 pages.

International Association of Scientific Hydrology (IASH) (1962): A legend for hydrogeological maps; Int. Assoc. Sci. Hydr., Publication No. 60, Gentbrugge, Belgium, 32 pages.

Le Breton, E. G. (1971): Hydrogeology of the Red Deer area, Alberta; Res. Coun. Alberta Rept. 71-1, 14 pages.

Ozoray, G. F. (1972): Hydrogeology of the Wabamun Lake area, Alberta; Res. Coun. Alberta Rept. 72-8, 17 pages.

Ozoray, G. F. (1974): Hydrogeology of the Waterways-Winefred Lake area, Alberta; Res. Coun. Alberta Rept. 74-2, 18 pages.

Ozoray, G. F. (in prep.): Hydrogeology of the Calgary area, Alberta.

Ozoray, G. F. and A. T. Lytviak (1974): Hydrogeology of the Gleichen area, Alberta; Alberta Res. Rept. 74-9, 16 pages.

Ozoray, G. F. and A. T. Lytviak (in prep.): Hydrogeology of the Namur Lake-Bitumount area, Alberta.

Ozoray, G. F. and A. T. Lytviak (in prep.): Hydrogeology of the Sand River area, Alberta.

Ozoray, G. F. and A. T. Lytviak (in prep.): Hydrogeology of the Pelican-Algar Lake area, Alberta.

Stein, R. (1976): Hydrogeology of the Edmonton area (northeast segment), Alberta; Alberta Res. Coun. Rept. 76-1, 21 pages.

Stevenson, D. R. and D. Borneuf (in prep.): Hydrogeology of the Medicine Hat area, Alberta; Alberta Res. Coun. Rept. 75-2.

Tokarsky, O. (1971): Hydrogeology of the Grimshaw-Chinook Valley area, Alberta; Res. Coun. Alberta Rept. 71-2, 19 pages.

Tokarsky, O. (1971): Hydrogeology of the Rocky Mountain House area, Alberta; Res. Coun. Alberta Rept. 71-3, 17 pages.

Tokarsky, O. (1972): Hydrogeology of the Bison Lake area, Alberta; Res. Coun. Alberta Rept. 72-2, 11 pages.

Tokarsky, O. (1972): Hydrogeology of the Mount Watt area, Alberta; Res. Coun. Alberta Rept. 72-3, 10 pages.

Tokarsky, O. (1974): Hydrogeology of the Lethbridge-Fernie area, Alberta; Res. Coun. Alberta Rept. 74-1, 18 pages.

Tokarsky, O. (in prep.): Hydrogeology of the Whitecourt area, Alberta; Alberta Res. Coun. Rept. 76-3.

Tokarsky, O. (in prep.): Hydrogeology of the Iosegun Lake area, Alberta; Alberta Res. Coun. Rept. 76-2.

Vogwill, R. (in prep.): Hydrogeology of the Lesser Slave Lake area, Alberta.

Vogwill, R. (in prep.): Hydrogeology of the Edson area, Alberta.

APPARENT TRANSMISSIVITY AND ITS DETERMINATION BY NOMOGRAM

by G. F. Ozoray

ABSTRACT

Apparent transmissivity values can provide a valuable indication of regional variations in relevant rock properties.

Apparent transmissivity is calculated from the duration and rate of pumping (bailing) and from the resulting total drawdown. Graphically, a straight line is substituted for the real drawdown curve and the starting point of the time scale is arbitrarily selected as 0.1 minute (because zero cannot be represented on the semilog paper). By definition, apparent transmissivity is then calculated with Jacob's modified non-equilibrium formula as follows:

$$T_{app} = \frac{264\ Q \log (10\ t)}{s}$$

where: T_{app} = apparent transmissivity in imperial gallons/day/foot (igpd/ft)

Q = pumping or bailing in imperial gallons/minute (igpm);

s = total drawdown in feet;

t = total duration of pumping or bailing in minutes.

A nomogram is presented which facilitates quick graphic determination of apparent transmissivity. The construction of the nomogram is explained and practical examples are given for its use.

BASIC CONCEPTS

Since 1968 a systematic program to map hydrogeologically the province of Alberta has been operative. During preparation of the maps use has been made of apparent transmissivity values.

Properly defined, transmissivity is the "product of the coefficient of permeability of the aquifer and the thickness of the aquifer. In actuality it is a measure of the flow capacity of an aquifer" (Badry, 1972). In other words, it is the rate of flow of water, in imperial gallons per day, through a vertical strip of aquifer one foot wide, extending the full thickness of the aquifer under a unit (1 ft/1 ft) hydraulic gradient.

Where geological conditions permit, transmissivity is calculated from the results of a production test (bail or pump test) in a well. An extended (if possible, one week long) pump test is preferred. In suitable conditions, Jacob's method (Ferris *et al.,* 1962) can be used to analyze the production test to give transmissivity. This method is described below.

During the pump test, drawdown (the water level decline in the well) is measured at appropriate time intervals. The measured drawdown data are plotted as a function of the logarithm of time on semi-logarithmic paper (Fig. 2.1). By extrapolation of the measured data, a curve can be drawn. Generally, after an initial period, the curve approaches a straight line through which a tangent can be drawn.

The slope of the tangent is constant over each logarithmic time cycle (for example from 1 to 10 minutes or from 1,000 to 10,000 minutes). From this and from the pumping rate the transmissivity is calculated (by Jacob's modified non-equilibrium formula):

$$T = \frac{264\ Q}{\Delta s}$$

where: T = transmissivity in imperial gallons per day per foot (igpd/ft);

Q = pumping rate in imperial gallons per minute (igpm);

s = drawdown in feet per log cycle of time (ft/log cycle).

(T igpd/ft x 1.725 x 10^{-7} = T cubic metres per second per metre.)

In most of Alberta, geological conditions are such that the use of Jacob's method is not truly valid scientifically, but in

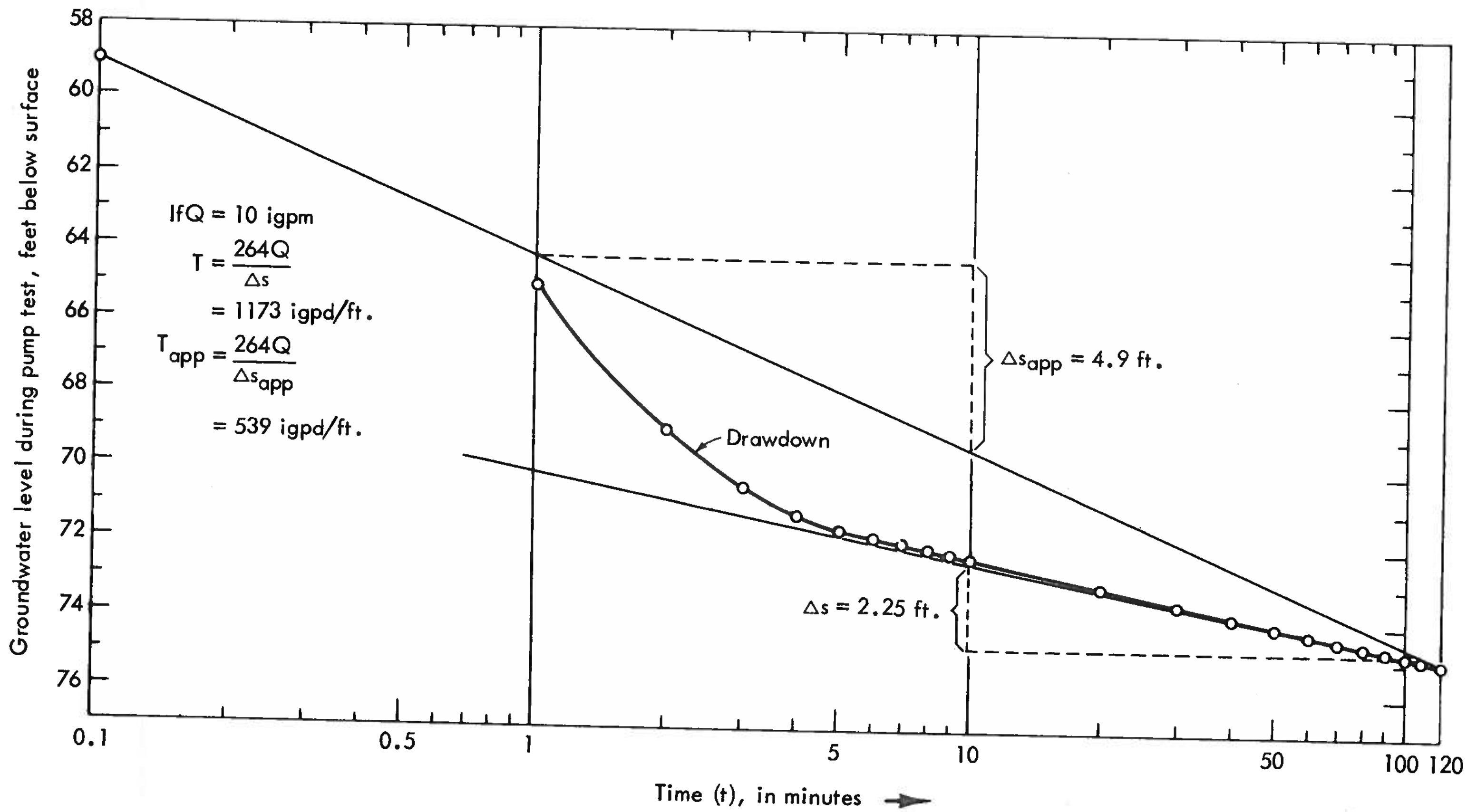


FIGURE 2.1 *Comparison between Δs (real rate of drawdown) and Δs_{app} (apparent rate of drawdown, ft/log cycle of minutes)*

the absence of suitable alternatives it is still employed. Even so, there are usually not enough transmissivity values based on proper pump tests. In many cases, however, wells are pumped or bailed by drillers for a short period of time for cleaning purposes or for an approximate yield test. From the duration and rate of pumping or bailing and from the resulting total drawdown an apparent transmissivity can be calculated (Farvolden, 1961). For a graphical solution (Fig. 2.1) a straight line is substituted for the real drawdown curve and the starting point of the time scale is arbitrarily selected as 0.1 minute. (Zero cannot be represented on the semilog paper.) Apparent transmissivity is then calculated using Jacob's modified non-equilibrium formula but replacing proper transmissivity by T_{app} as follows:

$$T_{app} = \frac{264\ Q \log(10\ t)}{s}$$

because: $T_{app} = \frac{264\ Q}{\Delta s_{app}}$

and $s_{app} = \frac{s}{\log(10\ t)}$

where: T_{app} = apparent transmissivity (igpd/ft);

Q = pumping or bailing rate (igpm);

s_{app} = apparent drawdown (ft/log cycle);

s = total drawdown (ft);

t = total duration of pumping or bailing (minutes).

Figure 2.1 shows a possible relationship between apparent transmissivity (T_{app}) and transmissivity (T). The figure is self-explanatory. True transmissivity depends only upon real aquifer conditions as reflected by the late segment of the drawdown curve. However, the value of apparent transmissivity is influenced, in addition, by factors outside of the aquifers (such as characteristics of the well and the pump). Apparent transmissivity is, therefore, only an approximation to the transmissivity value obtained from a pump test and may be less, the same, or greater.

Use of T_{app} in Hydrogeological Mapping

T_{app} values must be treated similarly to qualitatively evaluated geological parameters such as rock types. Instead of using a single data-point the tendency of several neighbouring apparent values in the same aquifer is considered.

Allowing for this, experience shows that apparent transmissivity values (if available in adequate number) give a valuable indication of regional variations in relevant rock properties (Ozoray, 1973). In the construction of the Wabamun Lake area hydrogeological map, (Ozoray, 1972) 619 T_{app} values were used to draw conclusions regarding yielding properties of rocks.

NOMOGRAM FOR DETERMINATION OF APPARENT TRANSMISSIVITY (T_{app})

Description of the nomogram

To facilitate quick graphic determination of T_{app} a nomogram (Fig. 2.2) has been constructed (Ozoray, 1970). The nomogram has a rectangular field and employs a system of rectangular coordinates.

Δs_{app} is plotted on the horizontal axis. Its dimension is ft/log cycle of minutes and increases to the right.

The vertical axis represents two values: s (drawdown) in feet and Q (production rate) in igpm. Scales for these values have been placed on opposite sides of the nomogram for the sake of clarity. The left vertical scale represents the drawdown values, with the origin in the lower left corner and values increasing upwards. The right vertical scale represents the production rate, with the origin in the upper right corner and values increasing downwards. For convenience, a "barrels-per-day" scale is also given.

Conversion factors are:

1 barrel = 35 imperial gallons

1 barrel per day = 0.024 igpm

1 barrel per hour = 0.58 igpm

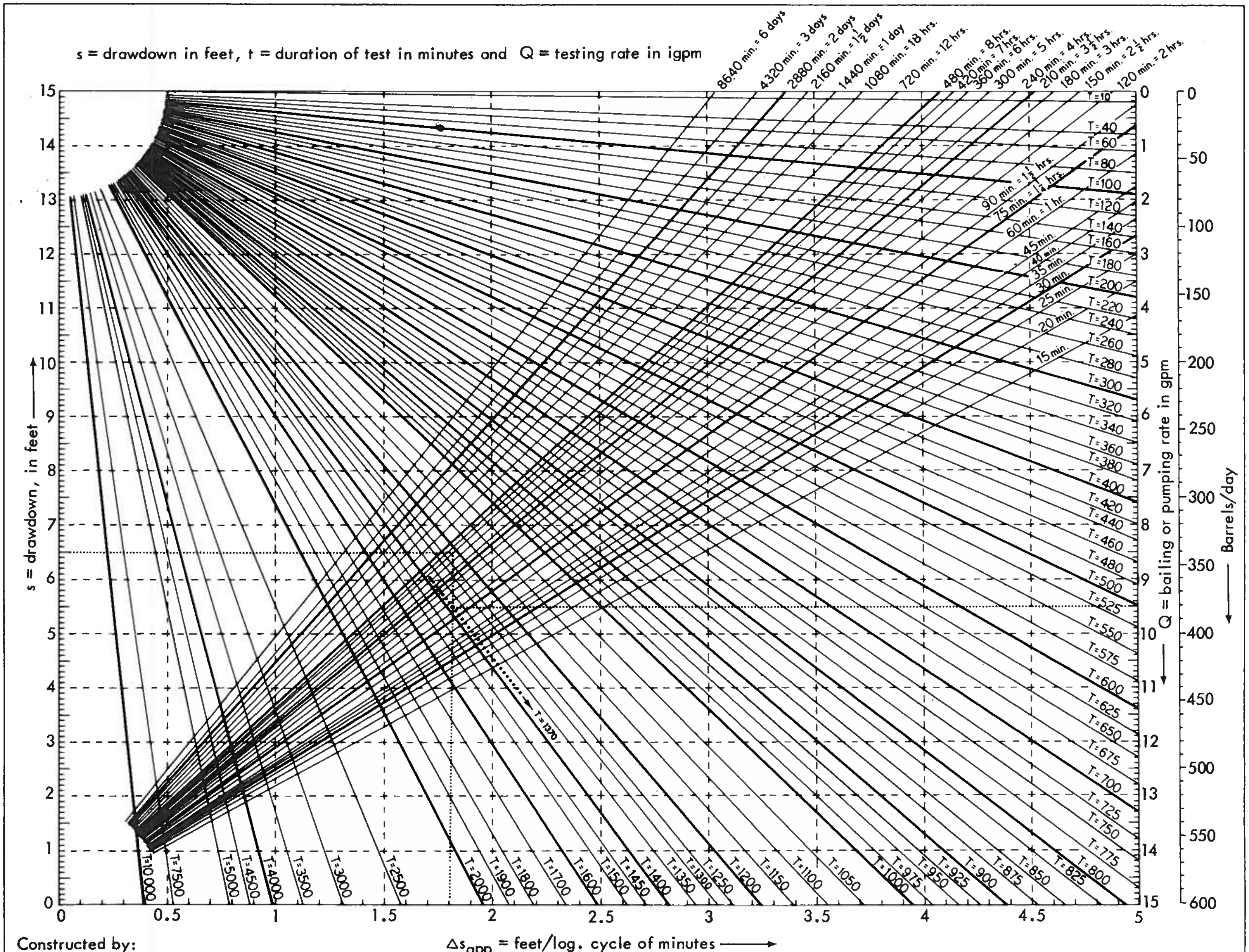
A family of lines, each of which represents a fixed time value with regard to the s and s_{app} coordinates originates in the lower left corner. Another family of lines originates in the upper left corner of the field. Each of these represents a value of T_{app}, with respect to the Q and Δs_{app} coordinates.

The use of the nomogram

To use the nomogram, measured values of s, t, and Q are required.

The first step is to locate the measured value of s on the left vertical axis and project this (perpendicular to the s axis) to the time line representing the measured value of t. A vertical line (perpendicular to the Δs_{app} axis and extending across the nomogram) is then projected through this point of intersection. (The intersection of this line with the s_{app} axis gives the relevant Δs_{app} value but this value is not needed further.)

Next, the Q value is located on the right vertical axis and projected, perpendicularly to the Q axis, to the Δs_{app} projection line determined above. The point of intersection of these two lines is the desired T_{app} value.



Constructed by:
G. Ozoray, Feb. 1969

Example: s = 6.5 feet
t = 6 hours
Q = 9.5 igpm T_{app} = 1374; reading ≈ 1370

FIGURE 2.2 Nomogram for determination of apparent transmissivity

A practical example (Fig. 2.2), using 6.5 feet, 6 hours, and 9.5 igpm for s, t, and Q respectively, is worked through in the following manner:

The 6.5 point on the s axis (left vertical) is projected to the 360 minute time line and through the resulting point of intersection a perpendicular to the Δs_{app} axis is drawn. This yields a Δs_{app} value of approximately 1.8 ft/log cycle.

A line is then drawn perpendicularly from the 9.5 igpm point on the Q axis to the Δs_{app} projection line. The intersection of these lines yields a T_{app} value of approximately 1370 igpd/ft. Comparison of this value to the numerically evaluated result of 1374 igpd/ft leads to the conclusion that the graphic method is sufficiently accurate for practical purposes.

Because of the low degree of accuracy of the basic data it is practical to round off T_{app} values of less than 200 to the nearest 10, values between 200 and 2,000 to the nearest 50, and values greater than 2,000 to the nearest 100.

Shifting of the decimal point

Shifting of the decimal point of s (drawdown) requires a shift in the same direction and by the same number of places in Δs_{app}. This means that the decimal point in the final result, that is, in T_{app}, is shifted in the opposite direction by the same number of places.

In the example cited, values of 6.5 ft, 360 min, and 9.5 igpm for s, t, and Q respectively yielded 1.8 ft/log cycle for Δs_{app} and 1370 igpd/ft for T_{app}. The changing of s to 65 and allowing t and Q to remain the same results in a Δs_{app} value of 18 ft/log cycle and a T_{app} value of 137 igpd/ft. The changing of s to 0.65 and again allowing t and Q to remain unchanged results in a Δs_{app} value of 0.18 ft/log cycle and a T_{app} value of 13,700 igpd/ft.

Shifting of the decimal point of Q (pumping rate) requires the decimal point to be shifted in the same direction and by the same number of places in T_{app}. If Q, for example, is changed to 0.95 igpm but s and t are allowed to remain at 6.5 ft. and 360 min respectively, then T_{app} is 137 igpd/ft. If Q is changed to 95 igpm and s and t are again unchanged, the T_{app} becomes 13,700.

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REFERENCES

Badry, A. (1972): A legend and guide for the preparation and use of the Alberta hydrogeological information and reconnaissance map series; Res. Coun. Alberta Rept. 72-12, 96 pages.

Farvolden, R. N. (1961): Groundwater resources, Pembina area, Alberta; Res. Coun. Alberta. Rept. 61-4, 26 pages.

Ferris, J. G., D. B. Knowles, R. H. Brown and R. W. Stallman (1962): Theory of aquifer tests; U.S.G.S. Water-Supply Paper 1536-E, 174 pages.

Ozoray, G. (1970): Nomogram for determination of apparent transmissivity; Res. Coun. Alberta Internal Rept., 4 pages.

Ozoray, G. (1972): Hydrogeology of the Wabamun Lake area, Alberta; Res. Coun. Alberta Rept. 72-8, 19 pages.

Ozoray, G. (1973): Groundwater mapping: a prerequisite of successful groundwater resource estimation and management; Proc., Int. Symp. on Development of Groundwater Resources, Madras, India, Vol. 1, p. 1-a. 1-8.

SAMPLING OF GROUNDWATERS FOR CHEMICAL ANALYSIS

by E. Wallick

ABSTRACT

Groundwater chemical systems are often unstable when exposed to surface conditions, so incorrect values for certain chemical parameters may result when samples are analyzed. Determination of the equilbrium chemical state of groundwater from the thermodynamic constants requires that input ionic concentrations be representative of field pressure and temperature conditions. Test samples from east-central Alberta showed that low values for hardness, alkalinity, and total iron were obtained if no attempt was made to preserve the samples. It was found that by collecting three samples — one untreated and one acidified to pH =1 for laboratory analysis and one untreated to field analysis of pH, temperature and conductivity, accurate determination of chemical components could be made.

INTRODUCTION

Proper sampling of groundwaters in chemical hydrology is necessary to minimize inaccuracies that may result from the effects of pressure and temperature changes within a sample between time of collection and subsequent analysis in the laboratory. Groundwater chemical systems are often unstable when exposed to surface conditions of temperature and partial pressures of CO_2 and O_2. This instability may lead to falsely low values for hardness, alkalinity, and total iron content, in addition to partial loss of trace elements. The purpose of this paper is three-fold:

1) to provide a brief simple understanding of the sources of chemical constituents of groundwater and the controls, if any, on solubility;
2) to present data that are indicative of the magnitude of change in groundwater chemistry between field and laboratory with respect to samples from east-central Alberta; and
3) to recommend the use of a simple method for preserving the field chemical state of groundwater that is particularly suitable in reconnaissance work where large numbers of samples must be collected under different conditions.

CHEMICAL EVOLUTION OF GROUNDWATERS

The concentrations of chemical constituents in groundwaters are controlled by the processes of dissolution and precipitation of sparingly soluble carbonates, sulfates, and highly soluble chlorides, and the weathering of silicate minerals. Modification of chemical composition occurs during groundwater flow in response to changing mineralogy, mixing of waters of different chemical type resulting in precipitation or dissolution of minerals, base exchange, and bacterial action.

The primary weathering cycle begins with the attack of CO_2* — charged soil water on silicate minerals. The feldspars (albite, anorthite, and microcline) are found in many resistate deposits, and take part in a series of weathering reactions of the type:

(1) $\text{feldspar} + H_2O + CO_2 \rightleftarrows \text{metal}^{+n} + n\,HCO_3^- + \text{kaolinite} + H_4SiO_4.$

Specific examples of these weathering reactions are given in table 3.1 together with expressions for the equilibrium constants. Most recent data (Paces, 1972; Garrels, 1975) indicate that groundwaters are not in chemical equilibrium with feldspars but tend toward equilibrium with Ca-montmorillonite, and amorphous alumina and silica. This explains why weathering feldspars become coated with clay minerals and release $Al(OH)_3$ and H_4SiO_4 in colloidal form.

Weathering of pyrite and other sulfides by oxidation is a primary source of SO_4^{-2} anion. Sulfates such as $CaSO_4.2H_2O$ (gypsum) and $Na_2SO_4.10H_2O$ (mirabilite) are therefore secondary, because their anions and cations have different primary sources. The same holds for calcite which ultimately must have precipitated from the equilibrium reaction —

(2) $Ca^{+2} + 2HCO_3^- \rightleftharpoons CaCO_3\downarrow + H_2O + CO_2\uparrow$

where all HCO_3 originated from atmospheric or plant CO_2, and Ca^{+2} was derived, for example, from anorthite. Dolomite is rarely precipitated from ordinary solutions, and occurs mainly as an alteration product wherein Mg^{+2} enters into solid solution with calcite to form $(Mg_xCa_{2-x})(CO_3)_2$.

The carbonate system is the most important control on the solubility of Ca^{+2}, Mg^{+2}, CO_2, and frequently Fe^{+2} in natural groundwaters. Table 3.2 summarizes the necessary

*CO_2 derived mainly from plant respiration and decomposition.

Table 3.1. Some Typical Silicate Weathering Reactions

albite⟶kaolinite

$$NaAlSi_3O_8 + H^+ + 4.5H_2O \rightleftharpoons 0.5Al_2Si_2O_5(OH)_4 + Na^+ + 2H_4SiO_4$$

$$\log K_{AK} = \log [Na^+]^* + 2 \log [H_4SiO_4] + pH = 0.046 + 0.00323T^{**}$$

microcline⟶kaolinite

$$KAlSi_3O_8 + H^+ + 4.5H_2O \rightleftharpoons 0.5\ Al_2Si_2O_5(OH)_4 + K^+ + 2H_4SiO_4$$

$$\log K_{MK} = \log [K^+] + 2 \log [H_4SiO_4] + pH = -2.931 + 0.01629T$$

anorthite⟶kaolinite

$$CaAl_2Si_2O_8 + 2H^+ + H_2O \rightleftharpoons Al_2Si_2O_5(OH)_4 + Ca^{+2}$$

$$\log K_{AnK} = \log[Ca^{+2}] + 2pH = 18.84 - 0.07114T$$

illite⟶kaolinite

$$K_{0.6}Mg_{0.25}Al_{2.30}Si_{3.5}O_{10}(OH)_2 + 1.1H^+ + 3.15H_2O \rightleftharpoons 1.15Al_2Si_2O_5(OH)_4 + 0.6K^+ + 0.25Mg^{+2} + 1.2H_4SiO_4$$

$$\log K_{IK} = 0.6 \log[K^+] + 0.25 \log[Mg^{+}] + 1.2 \log H_4SiO_4 + 1.1pH = 1.692 - 0.005086T$$

Ca-montmorillonite⟶kaolinite

$$\{6Ca_{0.167}Al_{2.33}Si_{3.67}O_{10}(OH)_2 + 2H^+ + 23H_2O \rightleftharpoons 7Al_2Si_2O_5(OH)_4 + Ca^{+2} + 8H_4SiO_4\}/6$$

$$6 \log K_{CaM\ K} = \log[Ca^{+2}] + 8 \log[H_4SiO_4] + 2pH = 0.01143T - 16.6$$

kaolinite⟶gibbsite

$$Al_2Si_2O_5(OH)_4 + 5H_2O \rightleftharpoons 2Al(OH)_3 + 2H_4SiO_4$$

$$\log K_{K\ G} = 2 \log[H_4SiO_4] = 0.02T - 8.79$$

*[ ] denotes thermodynamic activity.
**T in °C; constants after Helgeson (1969).

Table 3.2. Carbonate System Equilibria

Dissolution of CO_2 in pure H_2O

$H_2O + CO_2 \rightleftharpoons H_2CO_3$

$\log K_{CO_2} = \log[H_2CO_3] - \log P_{CO_2} = -13.417 + 2299.6/T + 0.01422T$ (Harned and Davis, 1943)

$= 3.44 \times 10^{-2}$ at T = 298°K

First Acid Dissociation

$H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$

$\log K_1 = -pH + \log[HCO_3^-] - \log[H_2CO_3] + 14.8435 - 3404.71/T - 0.03279T$ (Harned and Davis, 1943)

$= 4.43 \times 10^{-7}$ at T = 298°K

Second Acid Dissociation

$HCO_3^- \rightleftharpoons H^+ + CO_3^{-2}$

$\log K_2 = -pH + \log[CO_3^{-2}] = 6.498 - 2902.39/T - 0.02379T$ (Harned and Scholes, 1941)

$= 4.66 \times 10^{-11}$ at T = 298°K

Dissolution of Calcite (assuming existence of ion pairs $CaHCO_3^+$ and $CaCO_3$)

$CaCO_3 \rightleftharpoons Ca^{+2} + CO_3^{-2}$

$\log K_c = \log[Ca^{+2}] + \log[CO_3^{-2}] = 13.543 - 3000/T$ (Jacobsen and Langmuir, 1974)

$= 3.35 \times 10^{-9}$ at T = 298°K

Dissociation of Water

$H_2O \rightleftharpoons H^+ + OH^-$

$\log K_w = -(pH + pOH) = -14.00$ at T = 298° K and sufficient equilibria required to define the carbonate system. For normal rainwaters at 25°C and an atmospheric P_{CO_2} of 3.3×10^{-4} atm., the pH is about 5.6 and the total dissolved CO_2 content is about 10^{-5} molal. As total dissolved CO_2 in Alberta groundwaters is typically about 600 mg/l or approximately 10^{-2} molal, it is clear that higher values of P_{CO_2} and the presence of carbonate minerals are necessary to account for these values. Far higher bicarbonate concentrations can result during sulfate reduction.

(3) $$SO_4^{-2} + CH_4 \rightleftharpoons HS^- + HCO_3^- + H_2O$$

$$HS^- + H^+ \rightleftharpoons H_2S\uparrow$$

$$\text{or } Fe^{+2} + 2HS^- \rightleftharpoons FeS_2\downarrow + 2H^+$$

In the more arid regions of the province, where leaching depth is shallow due to high evaporative loss of infiltrating precipitation, the solution of gypsum derived from gypsiferous or pyritic bedrock may be an important source of calcium due to its presence in the shallow soil (generally below the C_{Ca} zone) and the higher solubility of gypsum (2080 mg/l at 25°C) as compared to that of calcite (14.3 mg/l at 25°C). However, the lower solubility of calcite effectively limits the concentration of Ca^{+2}.

Temperature Dependence of Equilibrium Constants

Chemical equilibrium constants are functions of temperature and pressure. At constant pressure, nominally 1 atmosphere, the relation of van't Hoff applies:

(4) $$\frac{d\ln K}{dT} = \frac{\Delta H_R}{RT^2}$$

or in integrated form,

$$\ln K = \frac{\Delta H_R}{R} \quad \frac{T_2 - T_1}{T_1 T_2}$$

where

$\Delta H_R = \Sigma\Delta H$ products $- \Sigma\Delta H$ reactants = change in enthalpy of the reaction;

R = gas constant;

T_1 = lower temperature } in degrees Kelvin
T_2 = upper temperature }

Examination of the expressions for equilibrium constants of the silicate and carbonate systems reveals the paramount importance of pH and temperature. The solubility of CO_2 in water is related inversely to temperature by means of K_{CO_2} (T) and directly to P_{CO_2}, the partial pressure of CO_2 in the soil or percolation medium. In addition, the pH of the system controls the dominance of H_2CO_3, HCO_3^-, CO_3^{-2} as shown in figure 3.1.

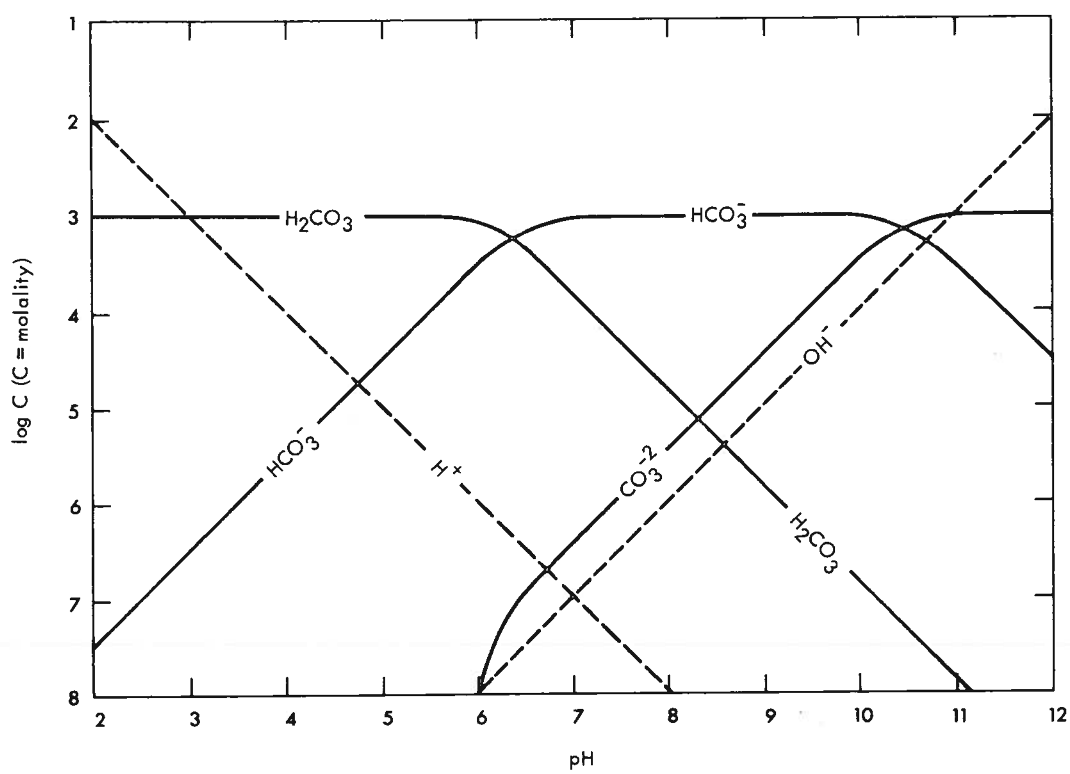


FIGURE 3.1 Carbonate species concentration (-log) versus pH for 10^{-3}M total concentration

Summary

The chemistry of moving groundwater is primarily a function of:

1) mineralogy of the medium through which it moves;
2) mean flow velocity, that is, residence time;
3) chemical kinetics = f(temperature, grain size);
4) antecedent composition; and
5) mixing of groundwaters of different chemical type.

Most (approximately 80-90%) of groundwater is dissipated in short local flow systems where the chemical groundwater system can be modelled as a two-stage process of rapid initial equilibration with calcite and clay minerals in the soil zone and slow reaction in the saturated zone. Equilibrium studies of groundwaters may, therefore, reveal the magnitude of chemical changes in the saturated zone because the processes of cation exchange, sulfate reduction, and mixing, all disturb equilibrium relationships.

CHEMICAL INSTABILITY OF GROUNDWATERS

When groundwater is withdrawn from a borehole or sampled from a spring, the water immediately becomes unstable because it is no longer in contact with the mineral matter of the aquifer, and is also subject to temperature and pressure changes that lead to loss of dissolved CO_2 and carbonate (Brown, Skougstad, and Fishman, 1970). To study the magnitude of such changes a field investigation of the groundwater chemistry in the Sand River area (NTS 73L) was carried out. During the study, samples were taken along a traverse from Vilna to Cold Lake. At each site three samples were collected:

1) one litre for field analysis
2) one litre for laboratory analysis
3) 250 ml acidified to pH 1, for laboratory analysis.

The field sample was analysed for pH, temperature, alkalinity, conductivity, and total iron content, and then was discarded. In the laboratory, the untreated sample was analyzed for Ca^{+2}, Mg^{+2}, Na^{+}, K^{+}, CO_2^{-2}, HCO_3^{-}, SO_4^{-2}, Cl^{-}, NO_3^{-}, F^{-}, $HSiO_4$, and pH. The acidified sample was tested for Ca^{+2}, Mg^{+2}, and total iron content.

RESULTS

Figure 3.2 is a plot of Ca^{+2} (mg/l) in the non-acidified sample against Ca^{+2} (mg/l) in the acidified sample. Note that the line of slope=1 serves as an upper limit for the points (analytical errors account for the few points located above the line). The loss of Ca^{+2} by precipitation is obvious and is of considerable magnitude in these waters if we can assume that acidification preserves the true concentrations.

Figure 3.3 is a plot of Mg^{+2} (mg/l) in the non-acidified sample against Mg^{+2} (mg/l) in the acidified sample. Scatter about the slope=1 line appears due to analytical errors alone, and no precipitation loss of Mg^{+2} appears to have occurred.

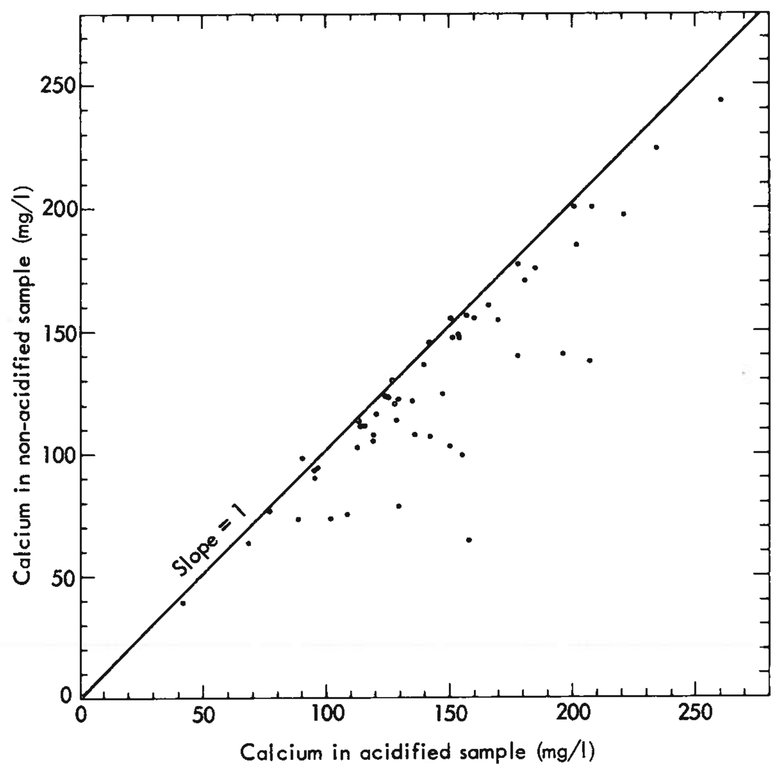


FIGURE 3.2 Calcium values in nonacidified samples versus calcium values in acidified samples

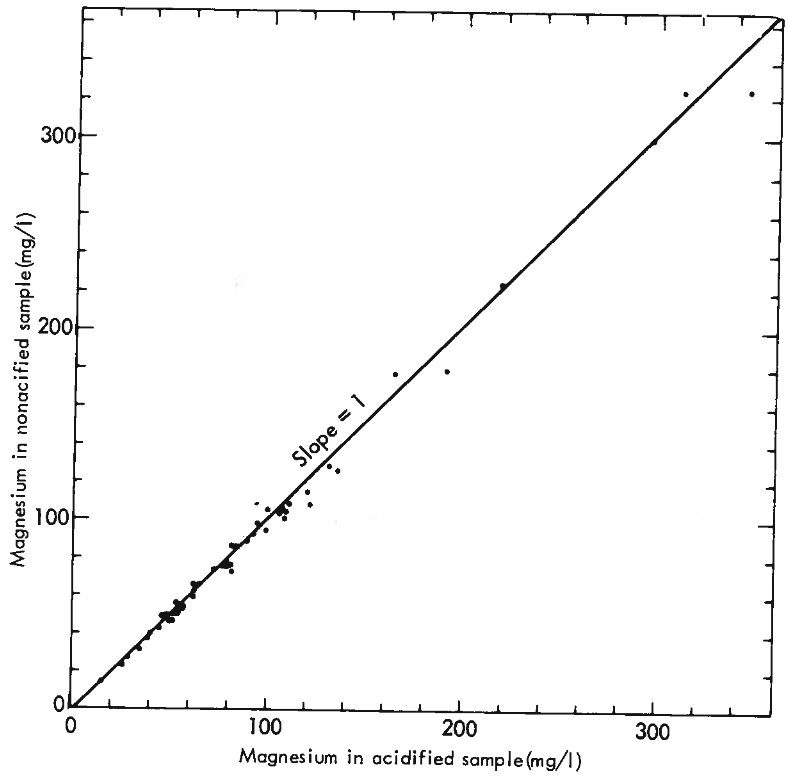


FIGURE 3.3 *Magnesium values in nonacidified samples versus magnesium values in acidified samples*

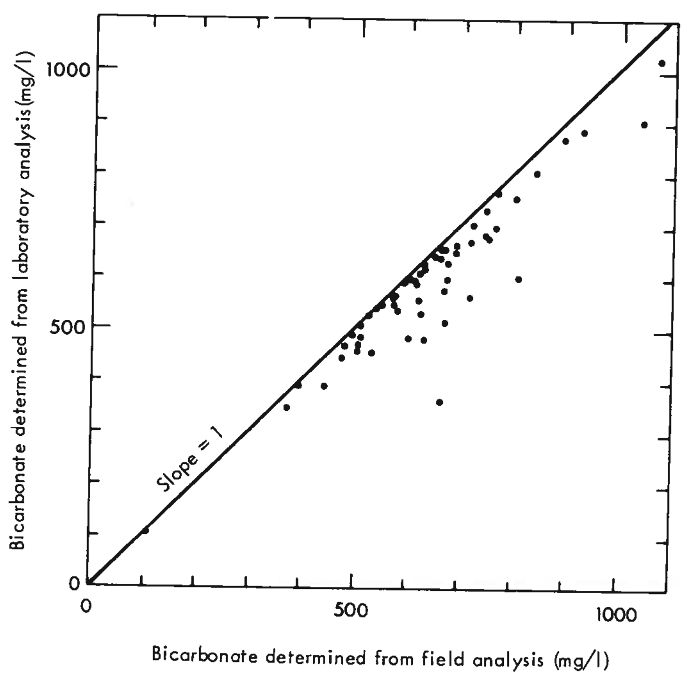


FIGURE 3.4 *Bicarbonate values from laboratory analysis versus bicarbonate values from field analysis*

Figure 3.4 clearly shows the loss of CO_2 from the non-acidified sample. The accuracy of the field alkalinity (expressed as HCO_3^- mg/l) determinations is surprisingly good, in view of the fact that all points lie on or below the line of slope=1.

Figure 3.5 is a plot of the laboratory pH minus field pH for each sample in the Sand River study. The lab pH was typically greater than the field pH, a finding consistent with CO_2 loss according to the equations:

(5a) $Ca^{+2} + 2HCO_3^- \rightleftharpoons CaCO_3\downarrow + H_2O + CO_2\uparrow$

(5b) $H^+ + HCO_3^- \rightleftharpoons H_2O + CO_2\uparrow$

(5c) $H^+ + CO_3^{-2} \rightleftharpoons HCO_3^-$

Hydrogen ion is used up as CO_2 leaves the system thereby decreasing a_{H^+} and increasing pH according to the equation:

(6) $pH = -\log_{10} a_{H^+}$

These results show a mean change in pH of about 0.5 pH unit; maximum excursions of more than a full pH unit can be expected.

Figure 3.6 is a similar plot of field minus laboratory conductivity. As conductivity is proportional to total dissolved solids, calibration of field and laboratory instruments facilitates detection of precipitation losses in groundwater samples. From this plot it is apparent that most samples lost conductivity between field and laboratory; gains in conductivity are ascribed to errors in measurement.

The implication thus far is that all three major changes in sample chemistry, that is increase in pH, and losses in Ca^{+2} and HCO_3^-, can be explained on the basis of calcite precipitation. The linear relationship between milliequivalents per litre (meq/l) HCO_3^- (field meq/l minus laboratory meq/l and meq/l of Ca^{+2} (field minus laboratory), as shown in figure 3.7, strongly suggests this.

The loss of HCO_3^- and Ca^{+2} from the non-acidified samples is substantial. Figures 3.8 and 3.9 show that as much as 300 mg/l HCO_3^- and 100 mg/l Ca^{+2} were lost from solution in the samples used in the study.

The Ca^{+2}/Mg^{+2} ratio is often used in groundwater studies as a qualitative indicator of age and direction of movement of groundwater. As has been shown previously Ca^{+2} precipitates preferentially to Mg^{+2}, and therefore inaccurate Ca^{+2} values result in "apparent aging" of groundwaters. Figure 3.10 demonstrates this, showing that (Ca^{+2}/Mg^{+2}) ratios are somewhat lower than the correct values for the bulk of non-acidified samples.

Figure 3.11 is a plot of total iron measured in the field against total iron as determined in the laboratory. The field

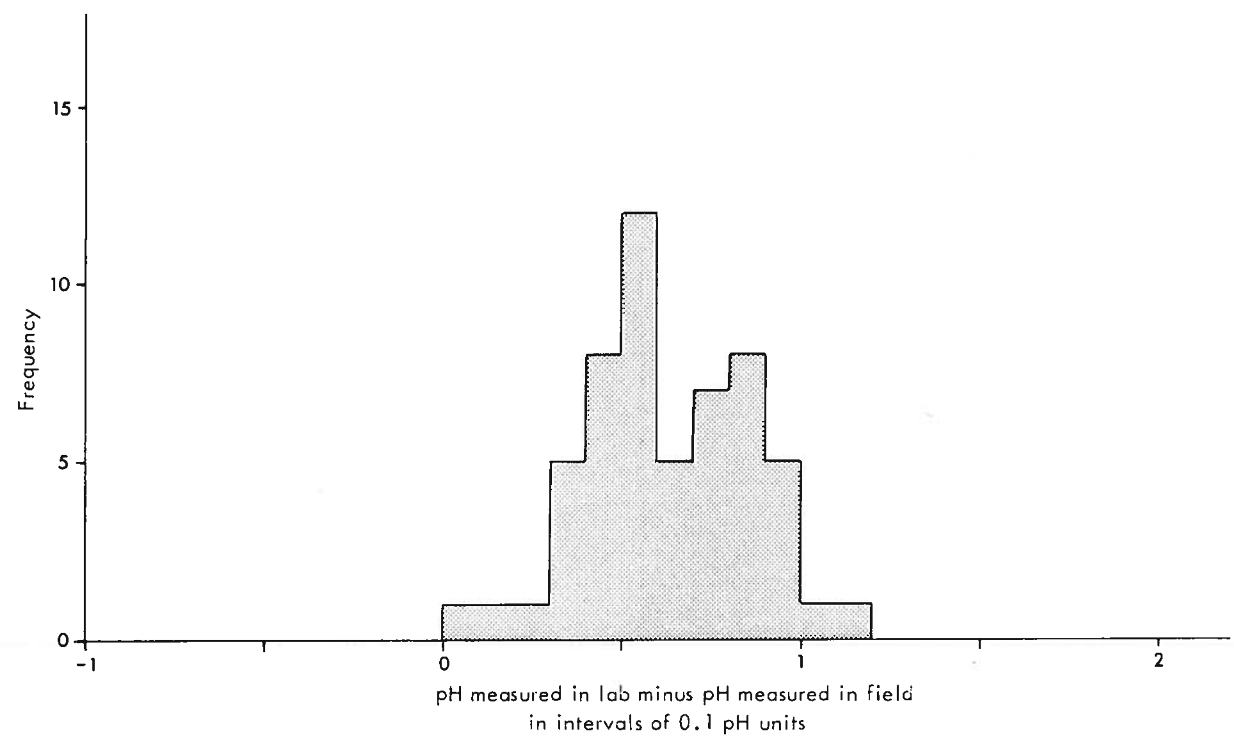


FIGURE 3.5 Frequency histogram of pH measured in the laboratory minus pH measured in the field

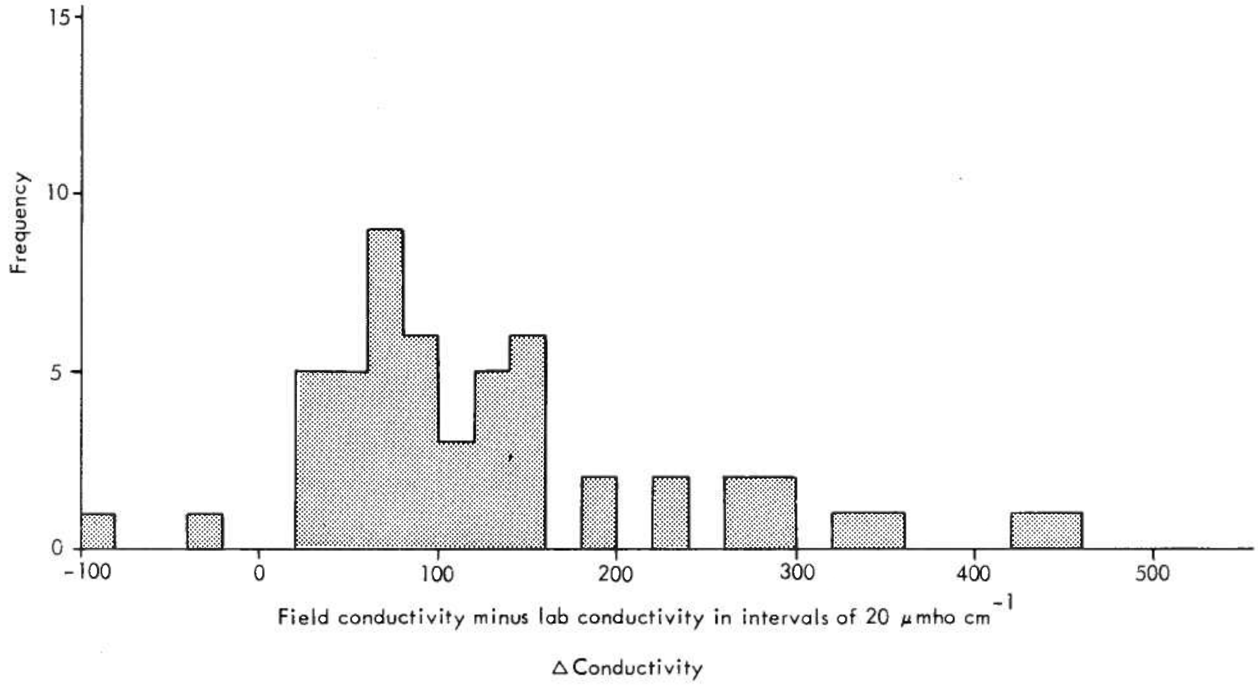


FIGURE 3.6 *Frequency histogram of field-measured conductivity minus laboratory-measured conductivity*

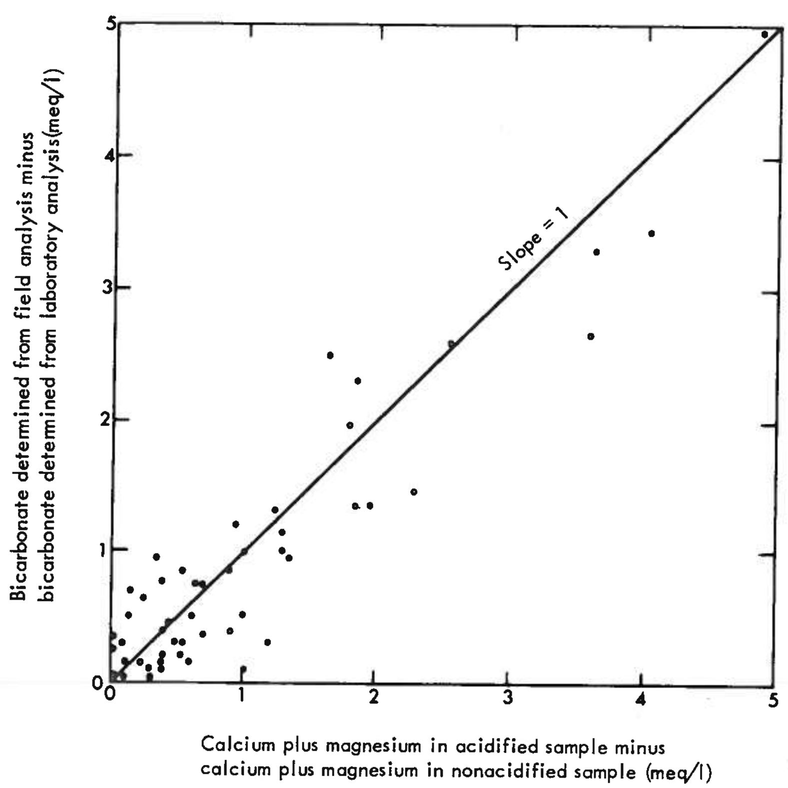


FIGURE 3.7 *Bicarbonate values versus calcium plus magnesium values*

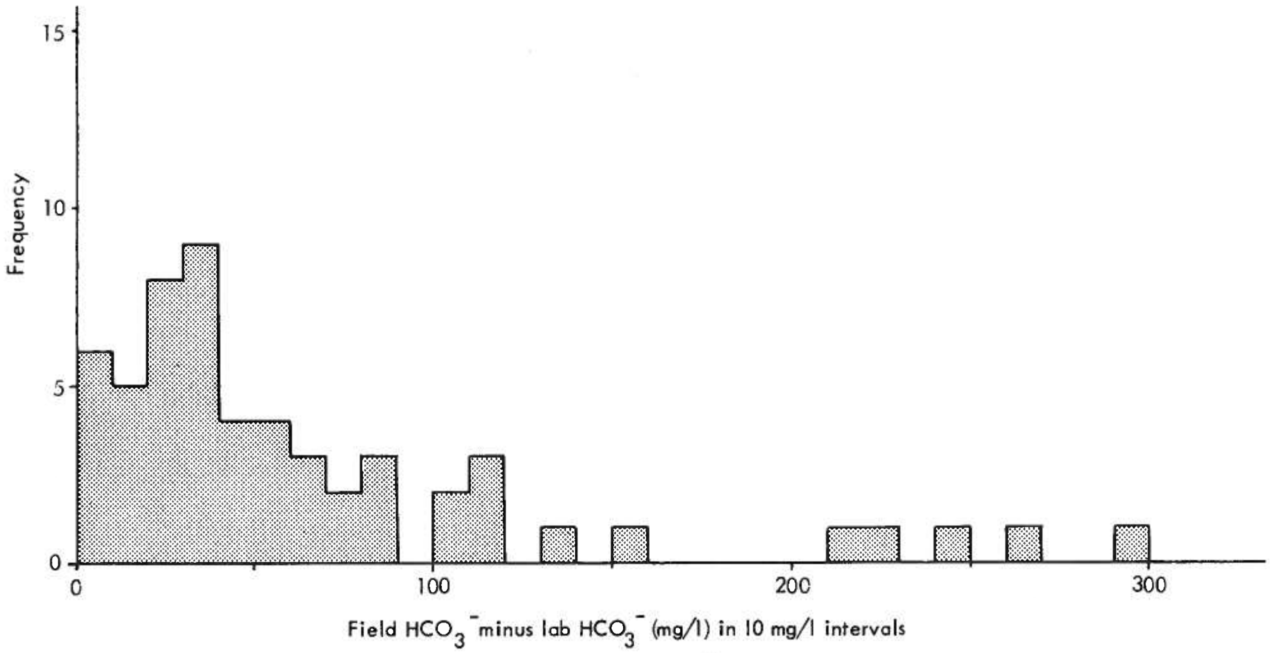


FIGURE 3.8 *Histogram of bicarbonate values from field analysis minus bicarbonate values from laboratory analysis*

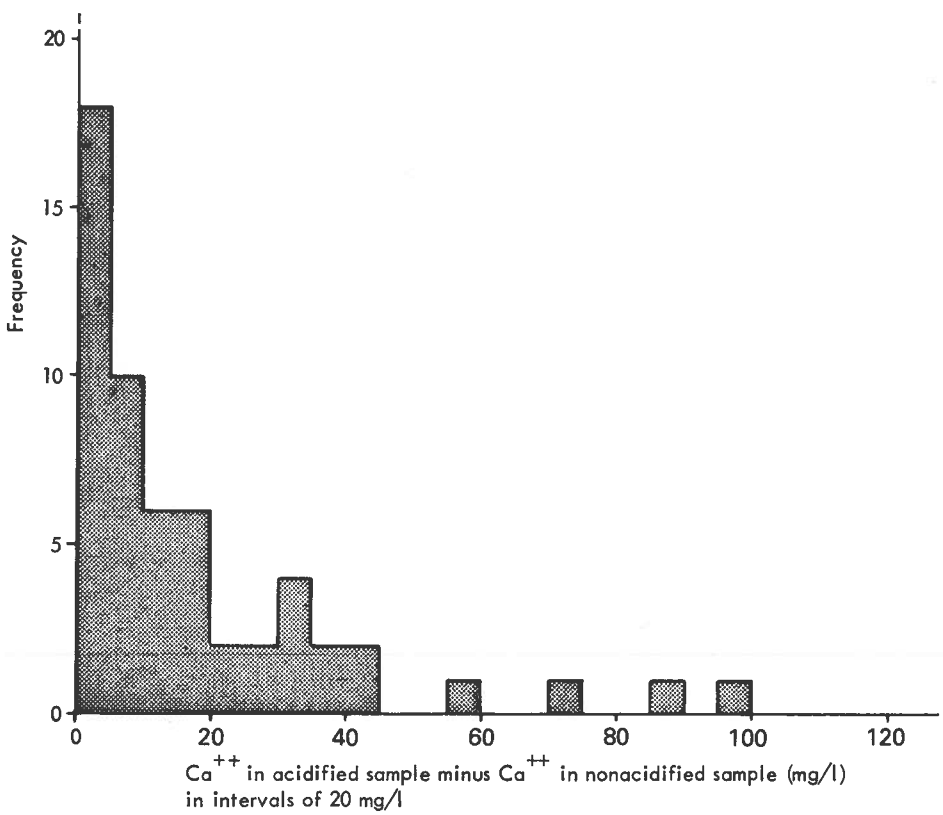


FIGURE 3.9 *Histogram of calcium values in acidified samples minus calcium values in nonacidified samples*

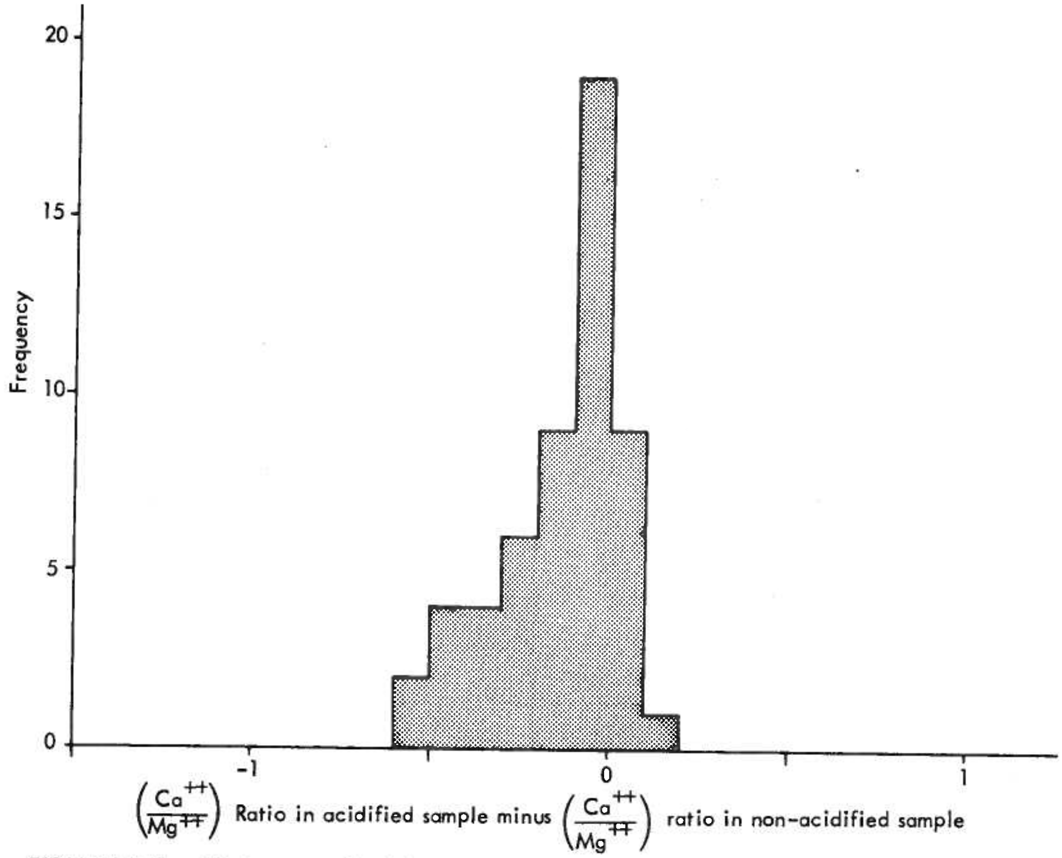


FIGURE 3.10 *Histogram of calcium to magnesium ratios in acidified samples minus calcium to magnesium ratios in nonacidified samples*

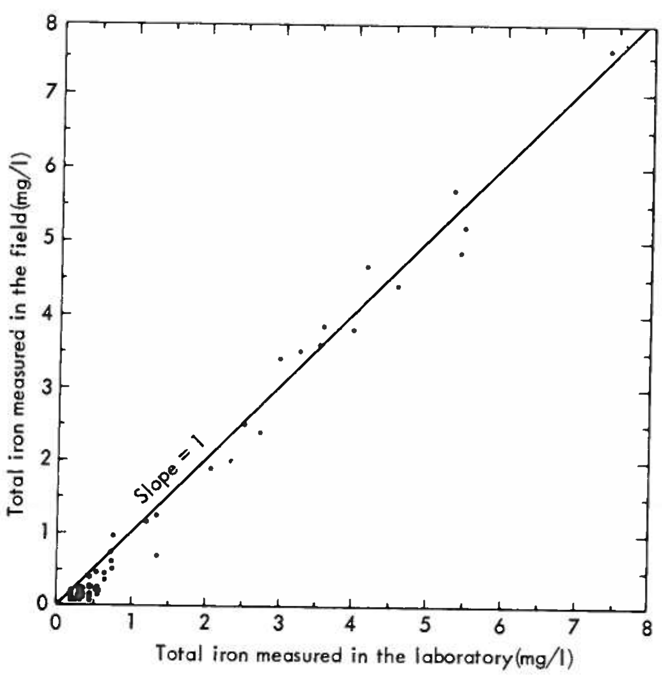


FIGURE 3.11 *Field measured total iron versus laboratory-measured total iron*

value was obtained by means of optical spectrometry on the non-acidified sample; the laboratory value was obtained by atomic absorption spectrometry on the acidified sample. The good linearity of the plot implies that iron does not precipitate rapidly (at least not within 15 minutes of sampling) from field samples. No detectable iron was found in the non-acidified samples upon laboratory analysis.

In conclusion, the following points should be considered important when attempting to preserve groundwaters so as to obtain accurate analytical data:

1) pH is valid only when measured at the time of sampling;
2) accurate alkalinity may be measured only in the field at the time of sampling;
3) or alkalinity may be preserved for laboratory analysis by storing the water sample at the temperature at which it was collected (which may be impractical) or by calculating the content of precipitated Ca^{+2} and Mg^{+2}(?) calcite from Ca^{+2} and Mg^{+2} contents in both acidified and non-acidified samples;
4) Ca^{+2} and Mg^{+2} (?) contents of non-acidified samples are suspect.
5) the content of total iron is valid only when determined in samples immediately upon collection, or subsequently in acidified samples;

RECOMMENDATIONS FOR HYDROCHEMICAL SAMPLING

Based upon this study, it is recommended that hydrochemical sampling follow the program outlined below.

Field Sampling and Analysis

Three samples should be collected at each site:
1) one litre of water filled to top of bottle;
2) one litre of sample, acidified to pH=1 (for example, 900 ml of sample and 100 ml of 1N HNO_3) with care taken to avoid acidification of clay suspensions, as the cation concentrations may increase due to leaching effects; samples from pumped wells should not be taken until clear, or in special cases a 0.45- M *millipore* filter should be used;
3) one litre of water for field measurement of pH, temperature, and conductivity, to be discarded upon completion of field analysis.

Laboratory Analysis

Non-acidified: Analysis for Ca^{+2}, Mg^{+2}, Na^{+}, K^{+}, HCO_3^{-}, CO_3^{-2}, SO_4^{-2}, Cl^{-}, pH, F^{-}, H_4SiO_4, conductivity.

Acidified: Analysis for Ca^{+2}, Mg^{+2}, Fe_{total}, trace elements as desired.

Computations

Corrections to the laboratory Ca^{+2}, Mg^{+2}, and HCO_3^{-} concentrations (mg/l) may be made using the following relationships in the case of calcium-magnesium type waters with pH less than 8.4:

1) $[Ca^{+2}]_{TRUE} = F_V \; [Ca^{+2}]_{ACID}$

2) $[Mg^{+2}]_{TRUE} = F_V \; [Mg^{+2}]_{ACID}$

3) $[HCO_3^{-}]_{TRUE} = [HCO_3^{-}]_{LAB} + 3.04([Ca^{+2}]_{TRUE} - [Ca^{+2}]_{LAB}) + 5.02\,([Mg^{+2}]_{TRUE} - [Mg^{+2}]_{LAB})$

4) $Alkalinity_{TRUE} = 0.82\,[HCO_3^{-}]_{LAB} + 1.7[CO_3^{-2}]_{LAB} + 2.5\,([Ca^{+2}]_{TRUE} - [Ca^{+2}]_{LAB}) + 4.1\,([Mg^{+2}]_{TRUE} - [Mg^{+2}]_{LAB})$

F_V = volume correction factor for dilution of water sample by 1N HNO_3, that is,

$$F_V = \frac{V_{ACID} + V_{WATER}}{V_{WATER}}$$

If concentrated (6N) HNO_3 is used, $F_V \simeq 1$, since only a few drops per litre are normally required for acidification to pH$\simeq$1.

ACKNOWLEDGMENTS

The author is grateful to K. Sadownyk and J. Littlewood for technical assistance and to B. Hitchon and R. Green for reviewing and editing the paper.

Note: For small water samples (<100ml) a method is available for preserving the field chemical state by combining equivalent known volumes of clear or filtered sample with a $BaCl_2$-HCl solution (prepared by diluting 5.09 g $BaCl_2.2H_2O$ plus 8.33 ml concentrated HCl to 1 litre with distilled water). The cation chemistry is determined by atomic absorption techniques and the sulfate concentration is determined by subtracting the barium remaining in solution from the added barium to yield the amount of $BaSO_4$ that precipitated. Excess chloride (equivalent to sample Cl^{-}) is determined by Mohr titration with $AgNO_3$ and alkalinity, pH, temperature, and conductivity are determined in the field (R. O. van Everdingen, personal communication, 1976).

REFERENCES

Brown, E., M. W. Skougstad, and M. J. Fishman (1970): Methods for collection and analysis of water samples for dissolved minerals and gases; *in* Techniques of Water-Resources Investigations of the U.S. Geological Survey, Book 5, Chapter A1, p. 14.

Garrels, R. M. (1975): Review of low temperature water mineral relations; Advisory Group on the Interpretation of Environmental Isotope and Hydrochemical Data in Groundwater Hydrology, Vienna, January, p. 27-31.

Harned, H. S. and R. Davis, Jr. (1943): The ionization constant of carbonic acid in water and the solubility of carbon dioxide in water and aqueous salt solutions from 0 to 50°C; J. Amer. Chem. Soc., Vol. 65, p. 2030-2037.

Harned, H. S. and S. R. Scholes Jr. (1943): The ionization constant of HCO_3^- from 0 to 50°C; J. Amer. Chem. Soc., Vol. 63, p. 1706-1709.

Helgeson, H. C. (1969): Thermodynamics of hydrothermal systems at elevated temperatures and pressures; Amer. J. Sci., Vol. 267, p. 729-804.

Jacobson, R. L., and D. Langmuir (1974): Dissociation constants of calcite and $CaHCO_3^+$ from 0 to 50°C; Geochim. Cosmochim. Acta, Vol. 38, p. 301-318.

Paces, J. (1972): Chemical characteristics and equilibrium in natural water-felsic rock-CO_2 system; Geochim. Cosmochim. Act, Vol. 36, p. 217-240.

CHARACTERISTICS OF PUMPING TESTS CONDUCTED IN HETEROGENEOUS CLASTIC SEDIMENTS OF THE EDMONTON AREA, ALBERTA

by R. Bibby

ABSTRACT

Drawdown curves of pumping tests conducted on 122 wells in the heterogeneous, clastic sediments of the Edmonton area have been classified on the basis of their shapes when plotted on a semilogarithmic scale. Four basic shapes are recognized. These do not, in general, conform to any theoretically predicted drawdown curves and no completely acceptable explanation is known to account for their shape.

The last straight-line slope of the drawdown curves (and therefore the short-term transmissive capacity as calculated by Jacob's equation) is shown to have a log-normal probability distribution. This is of considerable significance when drawdown curves are used for predictive purposes.

INTRODUCTION

The drawdown curves obtained from 122 pumping tests conducted in heterogeneous clastic sediments in the Edmonton area, Alberta, have a high degree of variability and commonly do not conform to any theoretically expected curve. The objective of this study is simply to describe and classify the drawdown curves as observed. No comprehensive explanation that accounts for the high degree of variability is known and none is attempted. In addition brief consideration is given to the way in which the drawdown curves are interpreted to obtain short-term transmissive capacities.

DESCRIPTION OF GEOLOGY, WELL COMPLETION AND PUMPING TESTS

Figure 4.1 shows the bedrock geology of the Edmonton map area. Superimposed on the geology are the locations of the wells that were pump tested.

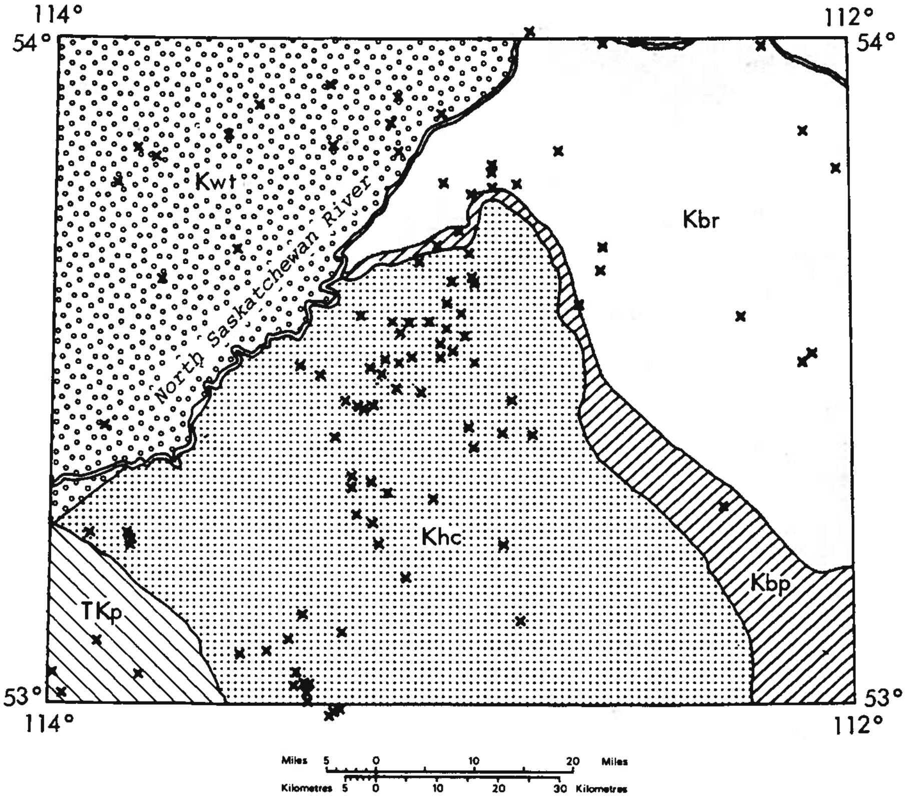
With the exception of the Bearpaw Formation, which is brackish and marine siltstone and shale, the bedrock is composed entirely of continental shales, sandstones, siltstones and coal seams, all of which are highly heterogeneous, lenticular, of variable thickness and laterally discontinuous. At all depths below the water table these sediments are fully saturated and hydraulically connected. Producing zones in the bedrock can occur in any of these lithologic types and are due to either intergranular or fracture permeability. However, the producing zone is typically of limited thickness and areal extent and can be regarded as a unit of relatively high permeability embedded in a matrix of low but significant permeability. The boundary between the two permeabilities, as discerned from pumping tests, is not distinct and cannot be modelled using concepts of barrier boundaries or leakage. One way in which it can be visualized is as a gradual facies change.

It is usual practice for drillers, completing wells in the bedrock, to drill until the first producing zone is encountered. The well is then completed by casing off the upper nonproducing zones and leaving the producing zone as an open hole or inserting a slotted liner against it. The amount of open interval in the completed well depends to some extent on the productivity of the zone encountered. If no distinct zone is encountered there may be as much as 200 feet (61 m) of open interval. With a particularly good producing zone the open interval may be simply the thickness of the zone.

The 122 pumping tests available to this study were almost all conducted on wells drilled for private individuals. The completion and development of the wells was entirely under the control of the drillers. The pumping tests were arranged through the cooperation of the driller and owner. The tests consisted usually of from 2 to 6 hours of pumping with readings taken in the pumping well only. Following the terminology of Bibby (in prep.), these tests are short-term pumping tests and permit the calculation of short-term transmissive capacity.

CLASSIFICATION OF DRAWDOWN CURVES

The time-drawdown data, when plotted on a semilog scale, usually starting at a time of one minute, form a curve which



LEGEND

× Location of Pump Test

TKp — Paskapoo Formation: thick bedded, calcareous, cherty sandstone; siltstone, and mudstone; minor conglomerate, thin limestone, coal and tuff beds.

Kwt — Wapiti Formation: clayey sandstone, bentonitic mudstone and bentonite, coal beds.

Khc — Horseshoe Canyon Formation: clayey sandstone, bentonitic mudstone and carbonaceous shale, coal and bentonite beds.

Kbp — Bearpaw Formation: shale and silty shale, clayey sandstone.

Kbr — Belly River Formation: thick-bedded sandstone, clayey siltstone, mudstone.

FIGURE 4.1 Bedrock geology and pump test locations in the study area consists of from one to three straight-line sections joined by quadratic sections. The curves have been classified according to the number of straight-line sections and the order of the relative gradients of these sections. Classification on this basis produced four distinct types of curves. These are illustrated in figure 4.2 where a diagrammatic curve is shown together with an example of each type. The types are defined in the figure and the number of occurrences of each type is given. Figure 4.3 shows the arithmetic average drawdown curve for each type. Each arithmetic average drawdown curve was composed in the following way:

1) For every straight-line section of the drawdown curve, the drawdown per log cycle at a pumping rate of unity (the unit slope) was calculated.

2) The arithmetic average of the unit slope of every straight-line section was calculated.

3) The average time and average drawdown at which every straight-line section began and ended were calculated.

4) The average drawdown curve was plotted using the average values of unit slopes, times and drawdowns.

The length measurement for drawdown and discharge measurement for pumping rate are arbitrary. In this study the drawdown was measured in metres (m) and the pumping rate in imperial gallons per minute (igpm).

In figure 4.4 the median drawdown curve of each type is shown. (The median of a set of values is the one in the middle position when the values are ordered by magnitude.) Each median curve was selected to be that curve in each class whose final unit slope is the median of all those occurring in the class.

The arithmetic average and median curves are both given because the slopes of the straight-line portions of the curves have a large variance and a skewed distribution. Thus, while the arithmetic average and the median are both average measures, they are not necessarily the same.

It can be seen that types 3 and 4 typically have significantly greater drawdown than types 1 and 2. On this basis they can be considered 'poor' wells. It should also be noted that the initial unit slopes of types 1, 3, and 4 are quite similar and that the final unit slopes of types 1 and 2 are also quite similar.

It is of interest to compare the four types of drawdown curves with that expected for a well in an aquifer which conforms to the Theis model. The drawdown for such a well is shown on a semilog scale in figure 4.5. It should be noted that for times at which the dimensionless parameter u is less than 0.01 the drawdown curve is a straight line. For times at which u is greater than 0.01 the drawdown curve deviates from this straight line in the manner shown.

The first drawdown measurement taken in the pumping tests in this study is usually at one minute and it is considered that in the majority of cases the value of u is less than 0.01 by this time, so that if the aquifers conformed to the Theis model a straight-line drawdown curve would be observed. The value of u cannot be calculated for the type of pumping test under consideration to verify this.

In actuality, because all of the tests are for pumping wells, there is also the 'well-loss' to take into account. This is the drawdown that occurs as a result of friction losses as water passes from the aquifer into the well and along the well-bore to the pump, and can be considered to be directly proportional to the square of the pumping rate. "Well-loss" is established in the early part of a test and in theory remains constant throughout. The occurrence of 'well-loss' is one reason why the storage coefficient, and hence the parameter u, cannot be computed from a pumping test conducted on a pumping well. The Theis-type drawdown curve with 'well-loss' is shown in figure 4.6. It is obvious that none of the four types of drawdown curves behaves similarly to the Theis curve. However, one way to relate the four types to the Theis model is to assume that each one behaves in the same manner as the Theis model for the duration of the first slope, then ceases to conform to the model because of heterogeneity.

The recovery curves for the pumping tests are not included in this report because they were recorded for only a minority of the tests. However, the recovery curve usually behaves in the way that would be expected if the final straight line of the drawdown curve was extrapolated beyond the duration of the test and an imaginary recharge well superimposed on this extrapolated portion having exactly the same shape as the observed drawdown curve. The shapes of the recovery curves when this is done are shown in figure 4.7. The behaviour of the recovery curves is taken to indicate that the shapes of the drawdown curves are determined by the aquifer and not by external influences such as well factors.

There is a possibility that one of the type curves represents an evolutionary or a rudimentary stage of another. For example, the type 4 curve could be later stage of type 3, or type 2 could be the same as type 1 but with the initial straight-line section indistinguishable. There are several possibilities, but no evidence to substantiate any one of them.

PROBABILITY DISTRIBUTION OF FINAL UNIT SLOPE

Figure 4.8 shows the frequency distribution of all values of final unit slope. These range from 0.001 to 100.0 metres per log cycle per igpm. The chi-square goodness-of-fit test was used to determine whether or not the values of final unit slope could be considered to have a log-normal probability distribution. The results of the test are given in table 4.1 which reveals that these values do in fact have such a distribution.

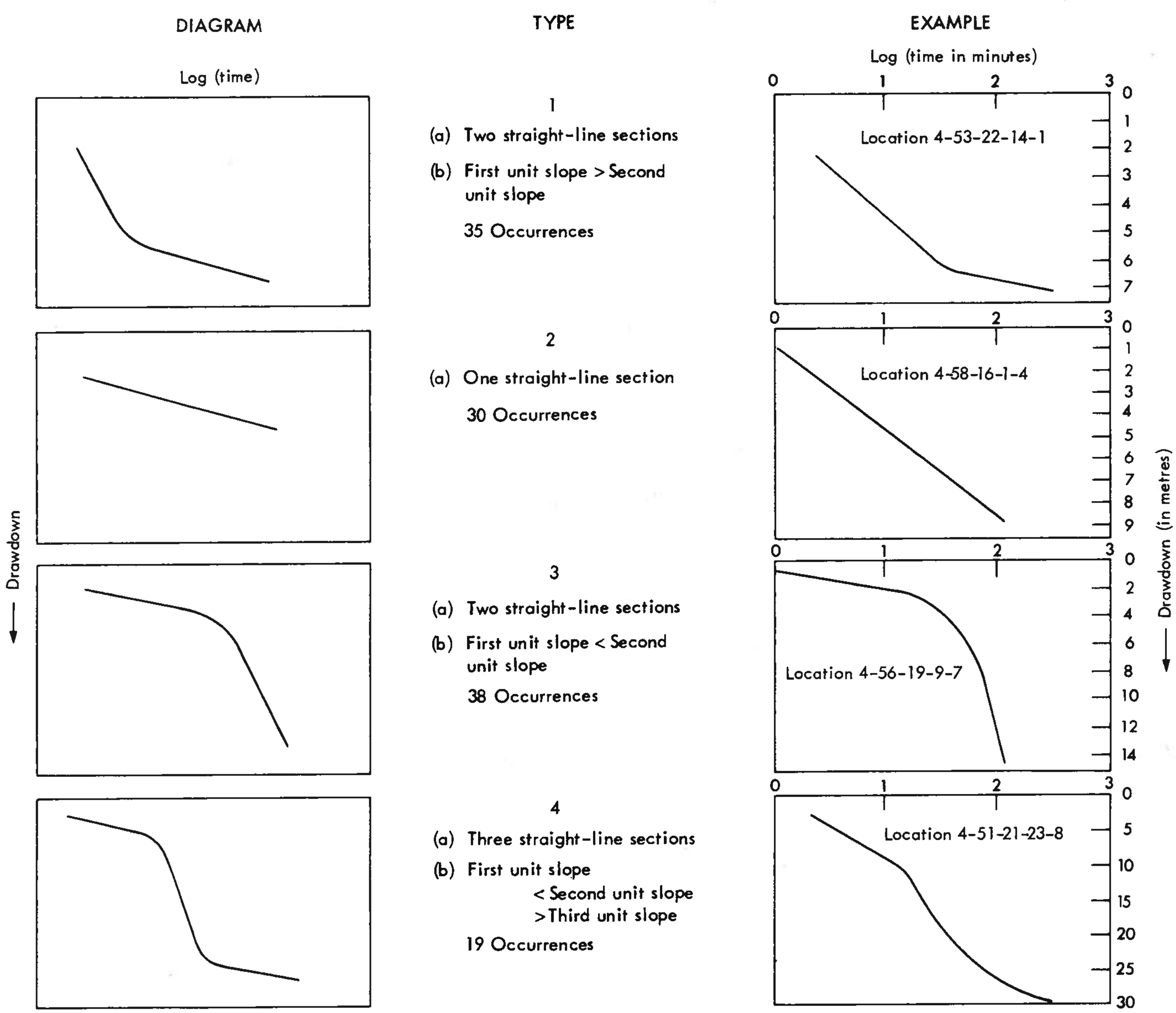


FIGURE 4.2 Diagrammatic type drawdown curves and examples

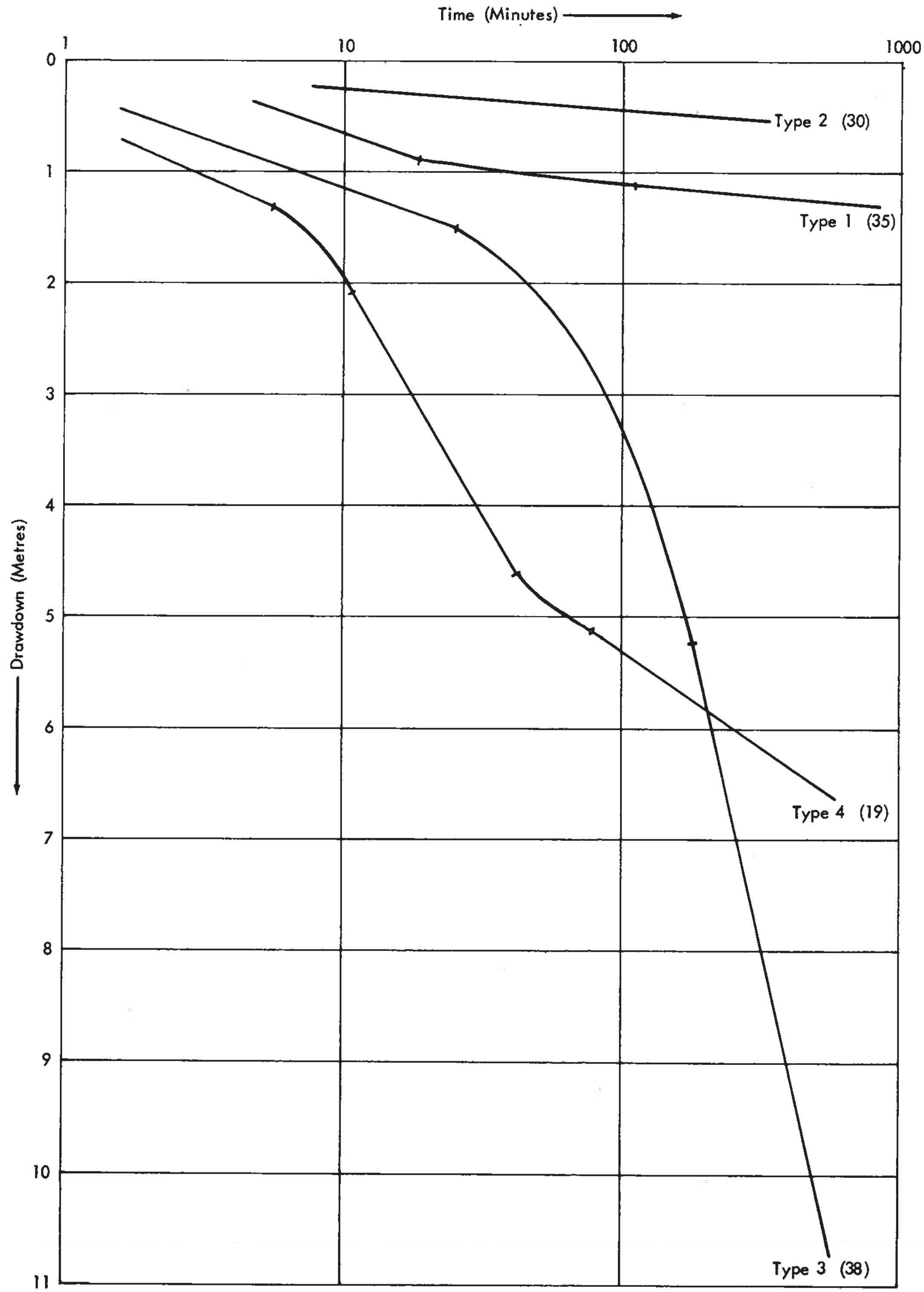


FIGURE 4.3 Arithmetic average drawdown curves for a unit pumping rate

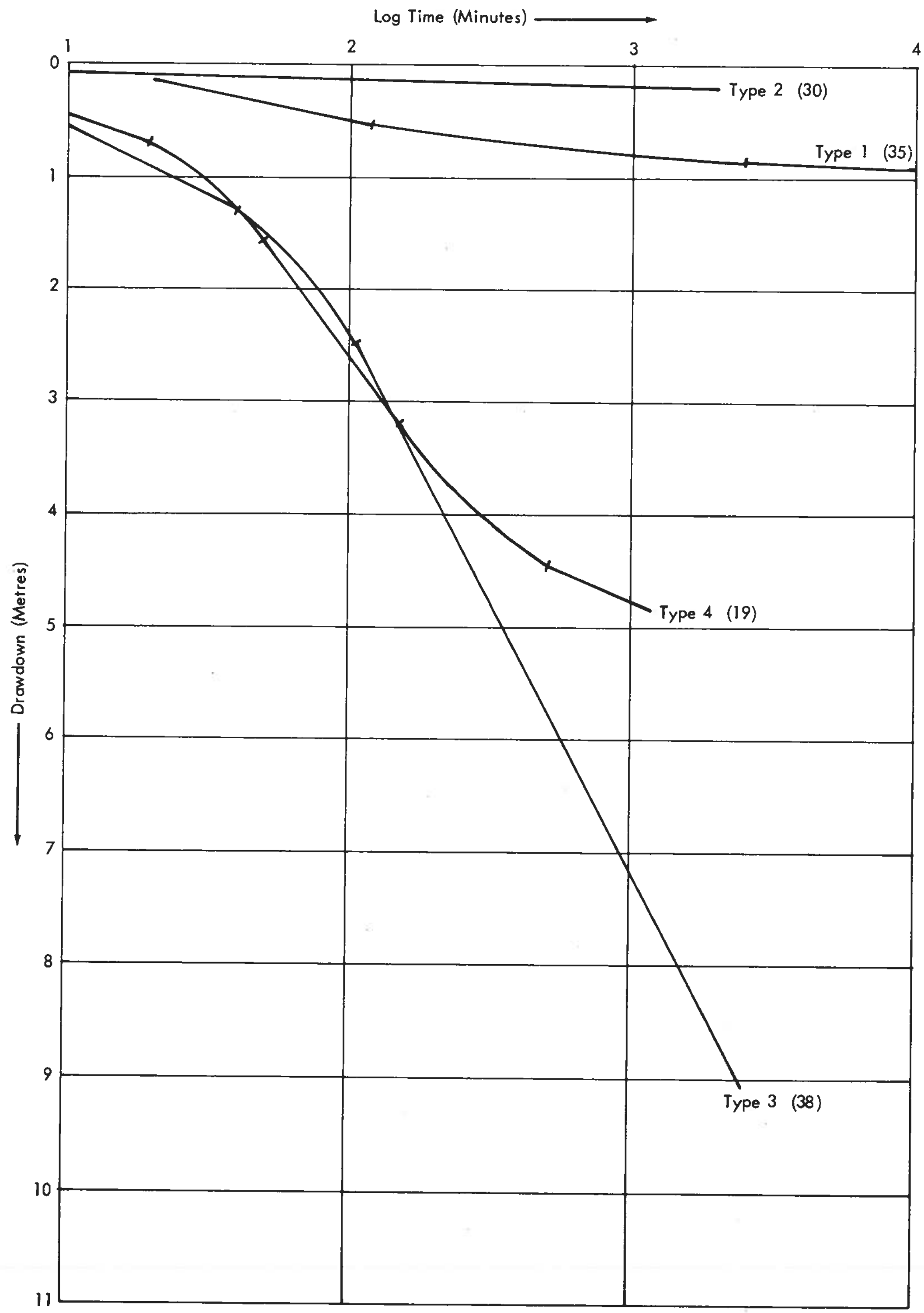


FIGURE 4.4 Median drawdown type curves for a unit pumping rate

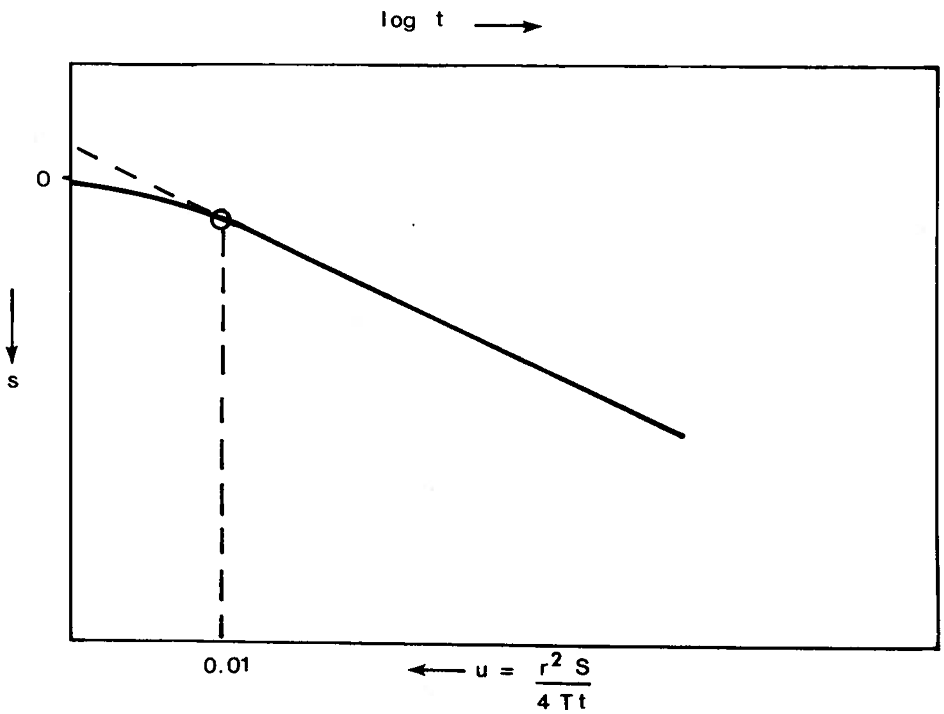


FIGURE 4.5 Drawdown curve, Theis model

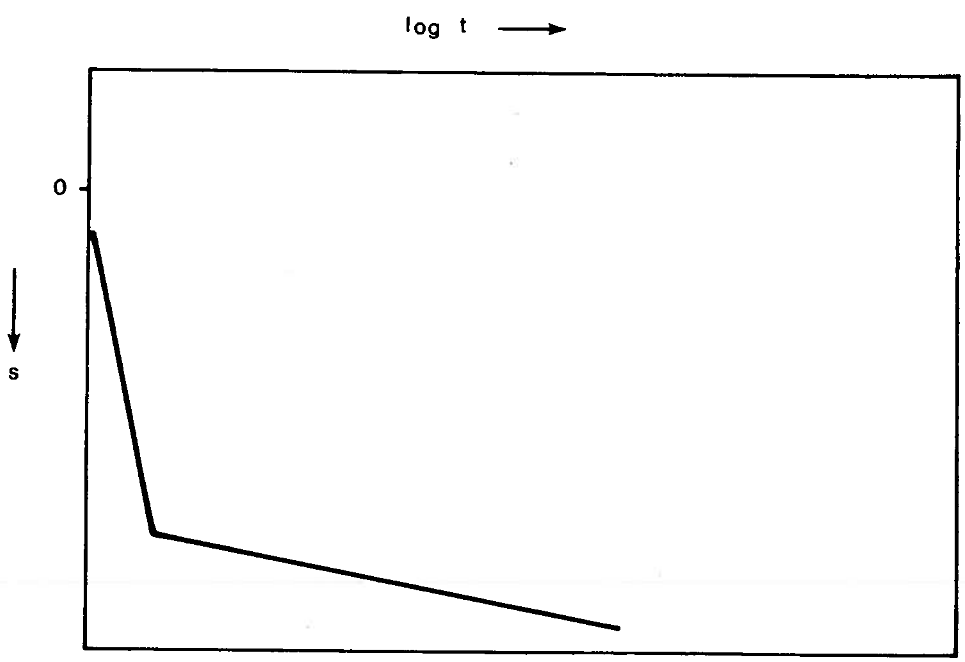


FIGURE 4.6 Drawdown curve, Theis model with "well-loss"

The usual practice, when analysing the drawdown curves of the type presented in the report, is to use Jacob's straight-line method on the final unit slope to calculate short-term transmissive capacities. The calculation is performed with the following equation:

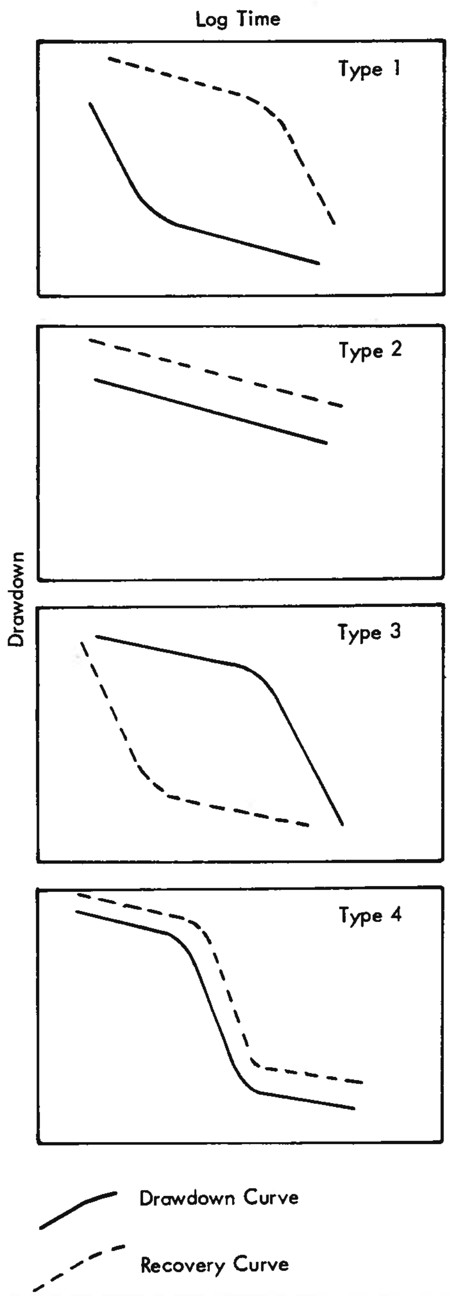


FIGURE 4.7 Typical recovery curves

$$\text{Short-term transmissive capacity} = \frac{80.5}{\text{final unit slope}}$$

where final unit slope is given in metres per log cycle per igpm.

It is apparent from the equation that if final unit slope has a log-normal distribution then short-term transmissive capacity will likewise. For completeness the results of a chi-squared test on the transmissive capacities are also presented in table 1.

This finding has particular significance when drawdown curves are used for predictive purposes. The problem facing hydrogeologists when predicting aquifer performance in heterogeneous sediments is that the only information available describes transmissive capacity conditions of short-term drainage volumes. What is needed to make a prediction is a description of the transmissive capacity conditions of the long-term drainage volume. This problem as it relates to the prediction of sustainable yields to wells, has been investigated and discussed by Bibby (in prep.).

ACKNOWLEDGMENTS

Nearly all of the pumping tests used as the basic data in this report were conducted as part of a reconnaissance mapping program of the Edmonton map area in 1972-73. The pump tests were made possible through the cooperation of a number of water well drillers and the well owners. Their assistance is greatly appreciated. A large proportion of the tests were conducted by W. N. Assmus, many as part of the mapping work of V. A. Carlson, G. M. Gabert and R. Stein. This report was critically read by G. M. Gabert and R. I. Vogwill.

REFERENCES

Bibby, R. (in prep.): Estimation of sustainable yield to a well in heterogeneous strata; Alberta Res. Coun. Bull.

Finney, D. J. (1941): On the distribution of a variate whose logarithm is normally distributed; Jour. Roy. Stat. Soc., London, Ser. B, V. 7, p. 155-161.

Green, R. (1972): Geological map of Alberta; Res. Coun. Alberta map, scale 1 in. to 20 mi.

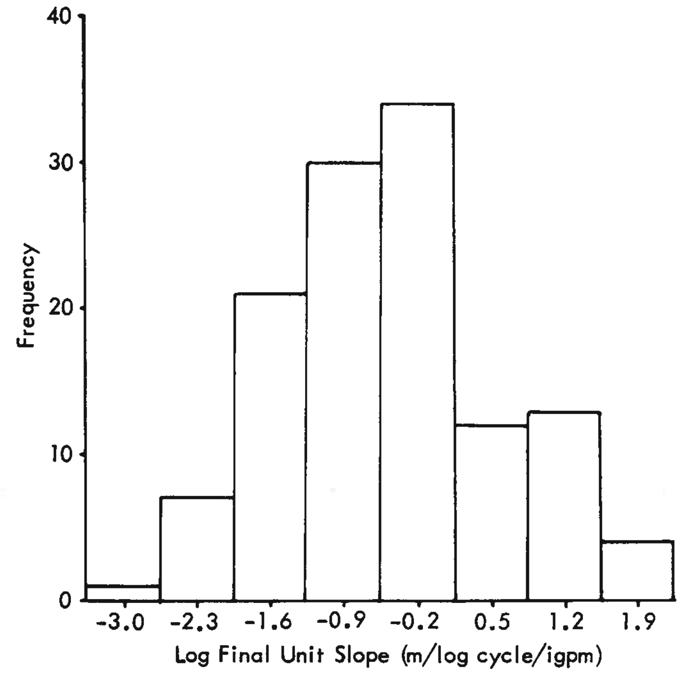


FIGURE 4.8 Histogram of final unit slope

Table 4.1 Chi-square test results of final unit slope and short term transmissive capacities

Logarithm of Final Unit Slope								
Mid-points of classes	-3.0	-2.3	-1.6	-0.9	-0.2	0.5	1.2	1.9
Frequency	1	7	21	30	34	12	13	4

Chi-square = 7.40
Degrees of freedom = 5
Probability = 0.19

Logarithm of Transmissive Capacity							
Mid-points of classes	0.7	1.4	2.1	2.8	3.5	4.2	4.9
Frequency	6	15	17	31	32	17	4

Chi-square = 6.58
Degrees of freedom = 5
Probability = 0.25

INVESTIGATION OF THE FEASIBILITY OF DEWATERING BURIED VALLEY SANDS TO AID SEWER-TUNNEL EXCAVATIONS, EDMONTON, ALBERTA

by G. M. Gabert

ABSTRACT

Excavation of a large-diameter sewer tunnel in the City of Edmonton was brought to a halt twice in 1973 because of the flow of saturated sand into the tunnel from the excavation front. A production well and observation wells were installed and an aquifer test was conducted to provide basic data to calculate the feasibility of dewatering buried valley sands overlying the tunnel. Conclusions showed:

1) that dewatering is feasible using 20 wells spaced 10 ft apart in an arrangement of two lines 30 ft apart paralleling and adjacent to each side of the position of the tunnel;
2) that well completions can be inexpensive and that each well would have to be pumped at 25 igpm or higher;
3) that at least 1 week or more of continuous pumping would be required.

INTRODUCTION

Excavation of a large-diameter sewer-tunnel in the southern part of the City of Edmonton was interrupted and brought to a halt twice in 1973 by a flow of saturated sand into the tunnel from the upper part of the excavation face. The first flow took place during the summer. The second flow occurred in the fall during this investigation and the results were observed by the author. In both cases the excavating equipment at the end of the tunnel was buried. The flows occurred either when the sands were directly encountered during excavation or when a thin layer of bedrock material between the tunnel and the overlying sands fractured. The potential for sand flows is expected to be minimized if the hydraulic pressure above the tunnel location is reduced by dewatering the sands or by reducing the head of water to the lower part of the sands. Following the first flow and in response to a request from the City of Edmonton concerning this problem, the Groundwater Division conducted test drilling, well performance tests, and aquifer performance tests to investigate the feasibility of dewatering buried valley sands overlying the tunnel.

PURPOSE OF FIELD INVESTIGATIONS

The purpose of performance tests conducted on wells completed in the buried valley sands was threefold:

1) to determine aquifer coefficients, particularly permeability;
2) to document the behavior of water levels in response to pumping a single well at a constant rate for a period of 1 week;
3) to determine the performance of the production well and an observation well.

SCOPE OF INVESTIGATION

The investigation was carried out in six stages:

1) Seven testholes were drilled along the direction of the tunnel and completed as observation wells.
2) A production well was completed on the basis of information obtained during test drilling.
3) A well performance test was conducted on the production well.
4) A long-term aquifer performance test was carried out using the production well and seven observation wells.
5) A well performance test and a short-term aquifer performance test were conducted on an observation well.
6) Basic data obtained from the field investigations were interpreted and predictions of water levels resulting from pumping three different arrangements of 20 wells (each well producing at 25 igpm for 1 week) were calculated.

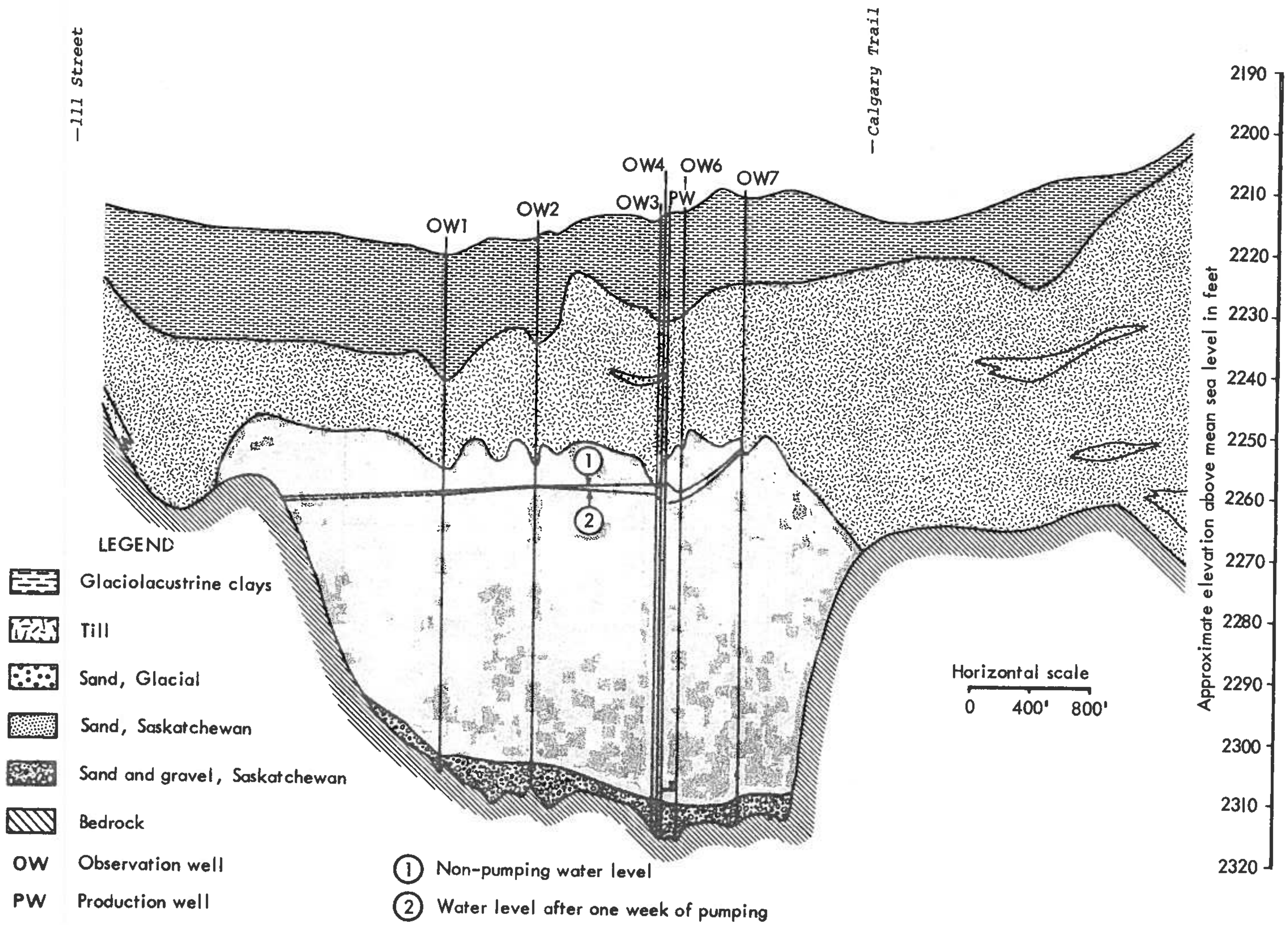


FIGURE 5.1 *Geological cross section along 30 Avenue tunnel (111 Street to Calgary Trail)*

GEOLOGY

Stratigraphy

A geological cross section along the 30th Avenue tunnel from 111th Street to the Calgary Trail is shown in figure 5.1. The tunnel is completed mainly in shale. The valley on the bedrock surface is filled with fine sand which contains thin, basal gravel layers consisting largely of concretions and quartzite pebbles. These deposits are known as Saskatchewan gravels and sands and were deposited prior to the first Quaternary glaciation (Stalker, 1968). Till containing minor layers of sand overlies the Saskatchewan sand. Glaciolacustrine clays and silts overlie the till and extend to the surface.

Engineering geology

The second flow of saturated sand into the tunnel caused a vertical collapse of overlying materials and resulted in a cavity about 25 ft in diameter at the surface and 15 ft deep (Plate 5.1). Plate 5.2 is a general view of the tunnel and plate 5.3 shows a view of the end of the tunnel after the upper part of the flow has been removed. The sand flowed into the tunnel from a small area of the roof and formed a wedge-shaped deposit with a volume of some 872 cu yd extending 150 ft along the tunnel. A time interval of several hours separated the flow of sand into the tunnel and the development of the cavity at the surface. An hypothesis of the sequence of events ending with the cavity at the surface is as follows:

1) Direct encounter of buried valley sands with excavating equipment, or collapse of a thin layer of bedrock existing between the tunnel roof and the base of the sand deposit.
2) Rapid flow of a large volume of saturated sand into the tunnel.
3) Development of a large cone-shaped depression in the sands extending up to the base of the till.
4) A gradual slumping of the more competent till into the depression in the sands.
5) Downward movement of the weaker glaciolacustrine deposits.
6) Development of a cavity at the surface.

The cavity at the surface was initially covered by a thin roof of surface deposits strengthened by compaction and plant roots. This roof slowly collapsed from the center outwards resulting in the cavity illustrated in plate 5.2.

In the tunnel workmen reported that until sand and water began to enter the tunnel about 7:20 AM on September 19 no water had entered the excavation area. The sand flowing into the tunnel slowed when the upper part of the wedge-shaped deposit reached the point of entry in the roof. Stabilization of the sand improved as water drained from the base of the sand wedge and after straw was impregnated into the advancing front of the flow. Although the amount of water draining into the tunnel increased somewhat after the flow of sand, it was not a problem. City

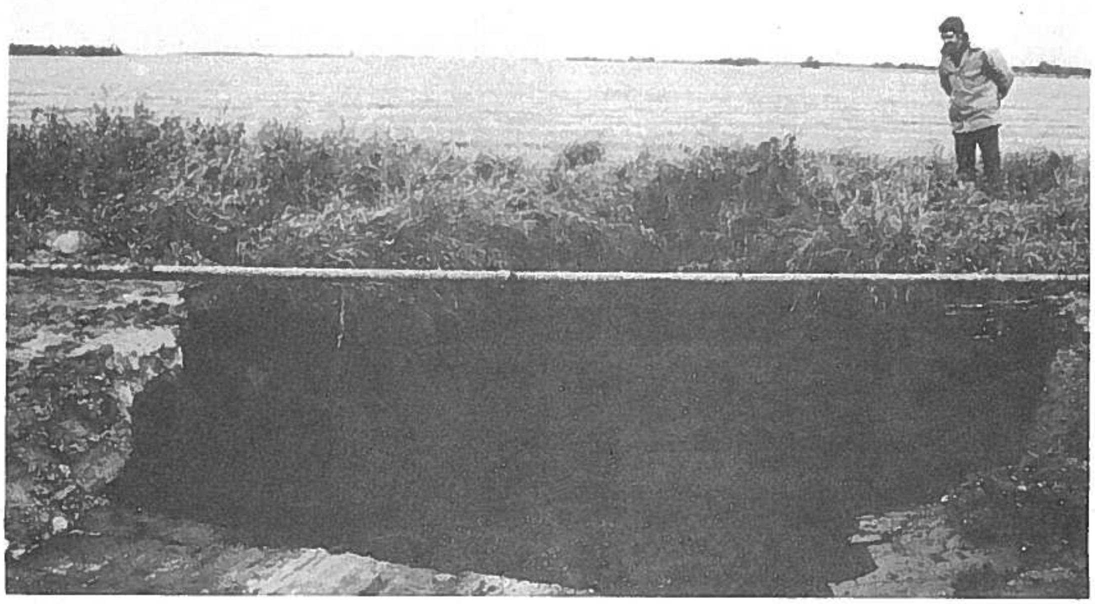


PLATE 5.1 View of cavity from surface

PLATE 5.2 View of tunnel

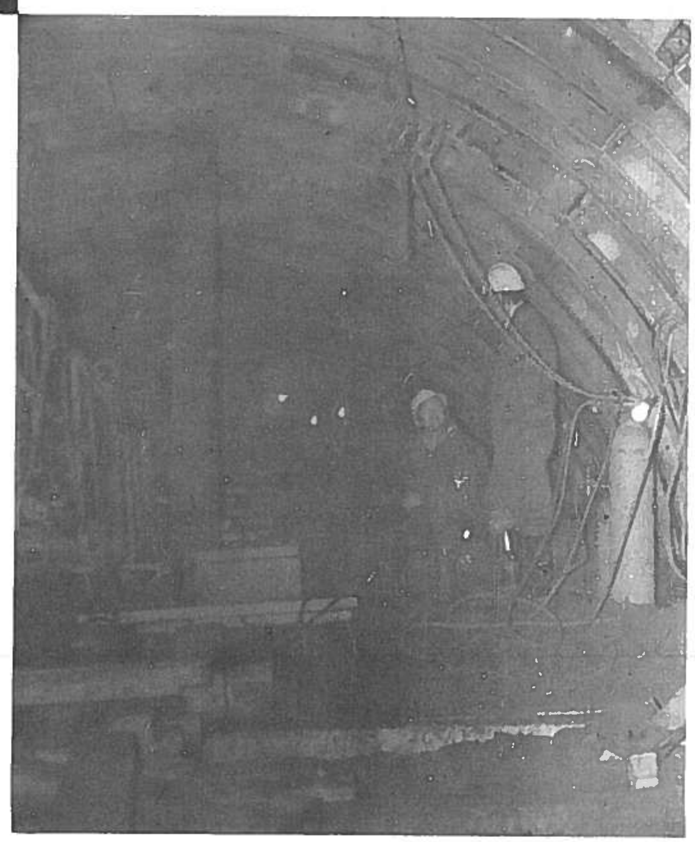


PLATE 5.3 View of sand deposit in tunnel

workmen partly excavated the top of the sand wedge and installed props to support the roof of the tunnel. This enabled repair and reinforcing of the roof (Plate 5.2). Excavation of the sand wedge from the tunnel to recover the excavating equipment was then undertaken.

A few days before the second flow of sand into the tunnel occurred, automatic water level recorders were installed on observation wells which had been completed to monitor water level fluctuations prior to and during pump testing (Fig. 5.2). The hydrograph for well 2 (Fig. 5.3), located near the end of the tunnel, shows that for a period of more than 2 days a sequence of sporadic rapid lowering of water level followed by recovery preceded the flow of sand into the tunnel. The type of response recorded on the hydrograph is interpreted as resulting from water entering voids created by fracturing of the bedrock overlying the tunnel roof. Water levels in observation wells 3, 4, 6 and 8 showed the same response as well 2. (Fig. 5.3) The hydrograph showed that water levels recovered and responded normally following the flow of sand into the tunnel (Fig. 5.3).

WELL COMPLETION DETAILS

The production well was designed using criteria presented by Ahrens (1957). Completion details for the production well and observation wells are shown in figure 5.4. Design of the production well was based on mechanical analysis of sand samples from the well obtained during normal drilling operations from depths of 87 to 97 ft. A continuous slot screen witn a slot width of 0.010 in was selected for installation in the well. This slot size allowed about 60 percent of the sand surrounding the screen to pass into the well during development. The well was designed to produce 100 igpm at an entrance velocity of 0.1 ft/sec. Development was completed with air.

Observation well 4 (Fig. 5.2), which was selected for pump testing, was completed with casing containing 32 slots per foot from 85 to 100 ft below surface. The slot dimensions are 0.030 in by 2 in. Slots in the observation well casing have straight sides but slots in the continuous slot screen of the production well enlarge inward in a V-shape. Observation wells produced 15 to 20 igpm while being developed with air.

PERFORMANCE TEST METHODS

Well performance tests

The performance of the production well (well 5) and observation well (Fig. 5.2) were evaluated separately by means of 4-stage step-drawdown tests. Each stage of the test was 1 hour long and pumping rates were increased instantaneously at the end of each hour from 8.3 to 13.2, 20.8, and 29.2 for the production well and from 12.5 to 18.3, 25, and 33.3 igpm for the observation well. The water level in each well was measured throughout the test.

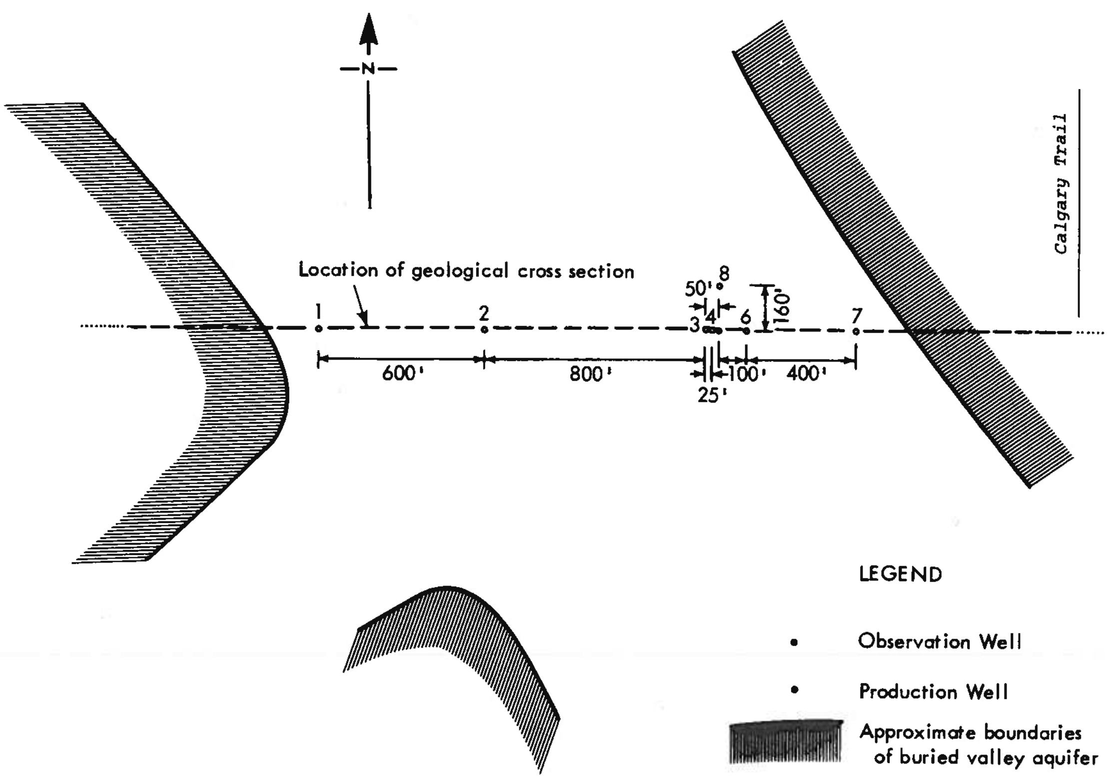


FIGURE 5.2 Location of wells for pumping test

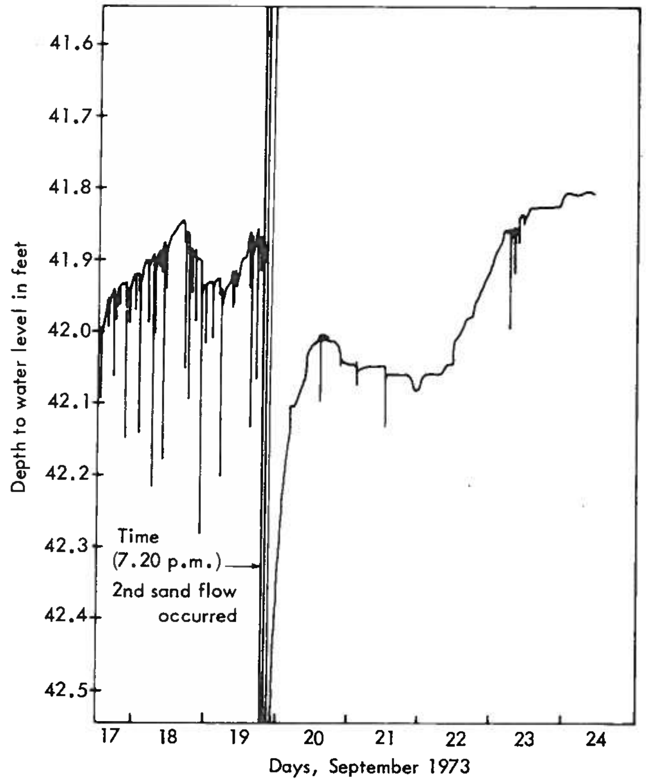


FIGURE 5.3 Hydrograph of observation well 2

Aquifer performance tests

The production well was pumped at a constant rate of 25 igpm for 1 week. Seven observation wells were completed to measure the response of water levels to pumping. The locations of the production well and observation wells with respect to boundaries of the buried valley aquifer are shown in figure 5.2. Water levels were measured with an electric tape in the production well and with automatic water level recorders in observation wells. A valve-controlled gauge was used to maintain a constant rate of pumping throughout the test. The recovery of water levels in all wells was measured in the same manner as the drawdown but for a shorter period of time.

An 8-hour aquifer performance test was conducted on observation well 4, using the production well and wells 3 and 6 as observation wells (Fig. 5.2). Well 4 was pumped at a constant rate of 33.3 igpm for the duration of the test. This test was conducted because results of a well performance test on the production well showed a large discrepancy between maximum design capacity and actual maximum capacity.

ANALYSIS, INTERPRETATION AND DISCUSSION OF DATA

Well performance tests

Analysis of the step-down data in the conventional manner was expected to give misleading results because gravity drainage of water in that portion of the sand aquifer dewatered during short periods of pumping had a stabilizing effect on water levels. However, specific capacities were calculated for the production rate of each step. The results are shown in table 5.1.

Figure 5.5 is a plot of specific capacities versus production rate for the production well (well 5) and observation well 4. The specific capacity of well 4 increases regularly to 4.38 igpm/ft at 33.3 igpm whereas that for well 5 levels off noticeably at slightly more than 2 igpm/ft when the production rate is greater than 15 igpm. The pumping rate was increased to 35 igpm in well 5 at the beginning of the fifth step during the step-drawdown test and resulted in the water level falling rapidly to the pump intake level which was below the bottom of the aquifer. Therefore, the optimum pumping rate for well 5 as it exists appears to be in the 20 to 30 igpm range whereas well 4 could be pumped at rates greater than 33.3 igpm. This result is rather paradoxical considering that well 4 has only 28.8 sq in of open area compared to 728 sq in for well 5.

The City of Edmonton tested the drainage effectiveness of 3-in and 4-in slotted pipe driven at an angle into the saturated sand above the roof of the tunnel. The pipe contained 32 slots over a length of 15 ft and slot dimensions were 0.030 in by 1 in. The open area of each drain pipe is therefore 14.4 sq in. The rate of flow of water was 13 igpm from the 3-in pipe and 100 igpm from the 4-in pipe. The

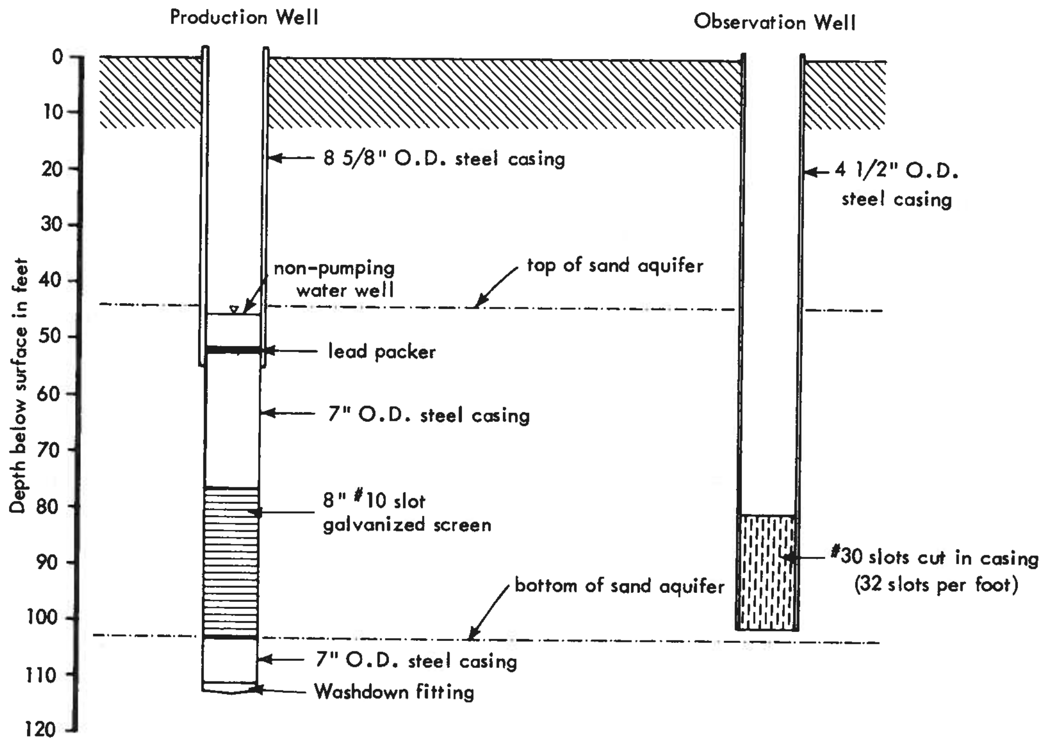


FIGURE 5.4 Well completion details

Table 5.1. Specific Capacities for Given Production Rates*

	Step No.	Production rate (igpm)	Drawdown (ft)	Specific capacity (igpm/ft of drawdown)
Observation Well (4)	1	12.5	9.07	1.38
	2	18.3	7.95	2.30
	3	25.0	6.60	3.79
	4	33.3	7.61	4.38
Production Well (5)	1	8.3	11.12	0.75
	2	14.2	7.44	1.91
	3	20.8	9.71	2.14
	4	29.2	14.02	2.08

*Calculated after one hour of production.

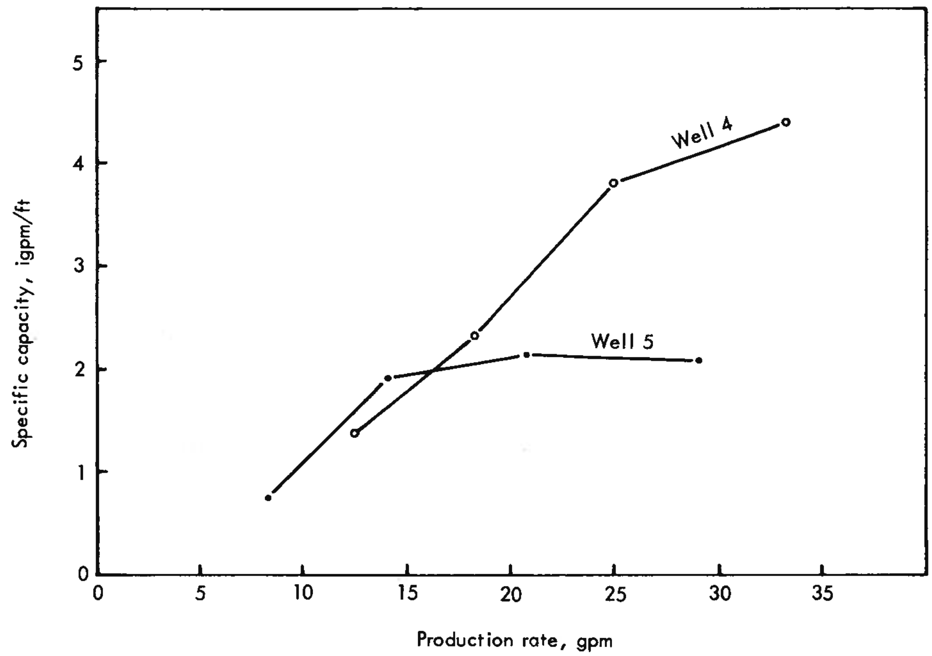


FIGURE 5.5 Specific capacity versus production rate for the production well

results of these tests and well performance tests show that the use of less expensive, slotted casing in completions is very effective.

Aquifer performance tests

The changes in water levels in the production well and observation wells 3, 4, 6 and 8 during the week-long test are shown in figures 5.6a to 5.6e. Time-drawdown data for the 8-hour test on observation well 4 are shown in figure 5.7. Analysis of data obtained from the long test were based on the assumptions that after 1 week of pumping equilibrium conditions existed in the aquifer near the production well, that no boundary effects influenced water levels, and that gravity drainage no longer significantly affected water levels. Permeability, k, was calculated from a form of the Thiem equation (Edward E. Johnson, Inc., 1966):

$$K = \frac{1055Q \log \frac{r_2}{r_1}}{(h_2^2 - h_1^2)}$$

for equilibrium conditions in an unconfined aquifer. In the above equation:

K = permeability, in igpd/ft 2 ;
Q = pumping rate, in igpm;
r_1 = distance to nearest observation well, in ft;
r_2 = distance to farthest observation well, in ft;
h_1 = saturated thickness at nearest observation well, in ft;
h_2 = saturated thickness at farthest observation well, in ft.

Table 5.2 below is a tabulation of the results of permeability determinations for the week long and 8-hour aquifer performance tests.

The relatively consistent values of permeability show that the aquifer response was similar for both aquifer perfor-

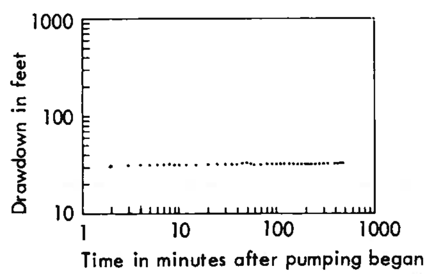


FIGURE 5.7 Time-drawdown graph of water level in well 4

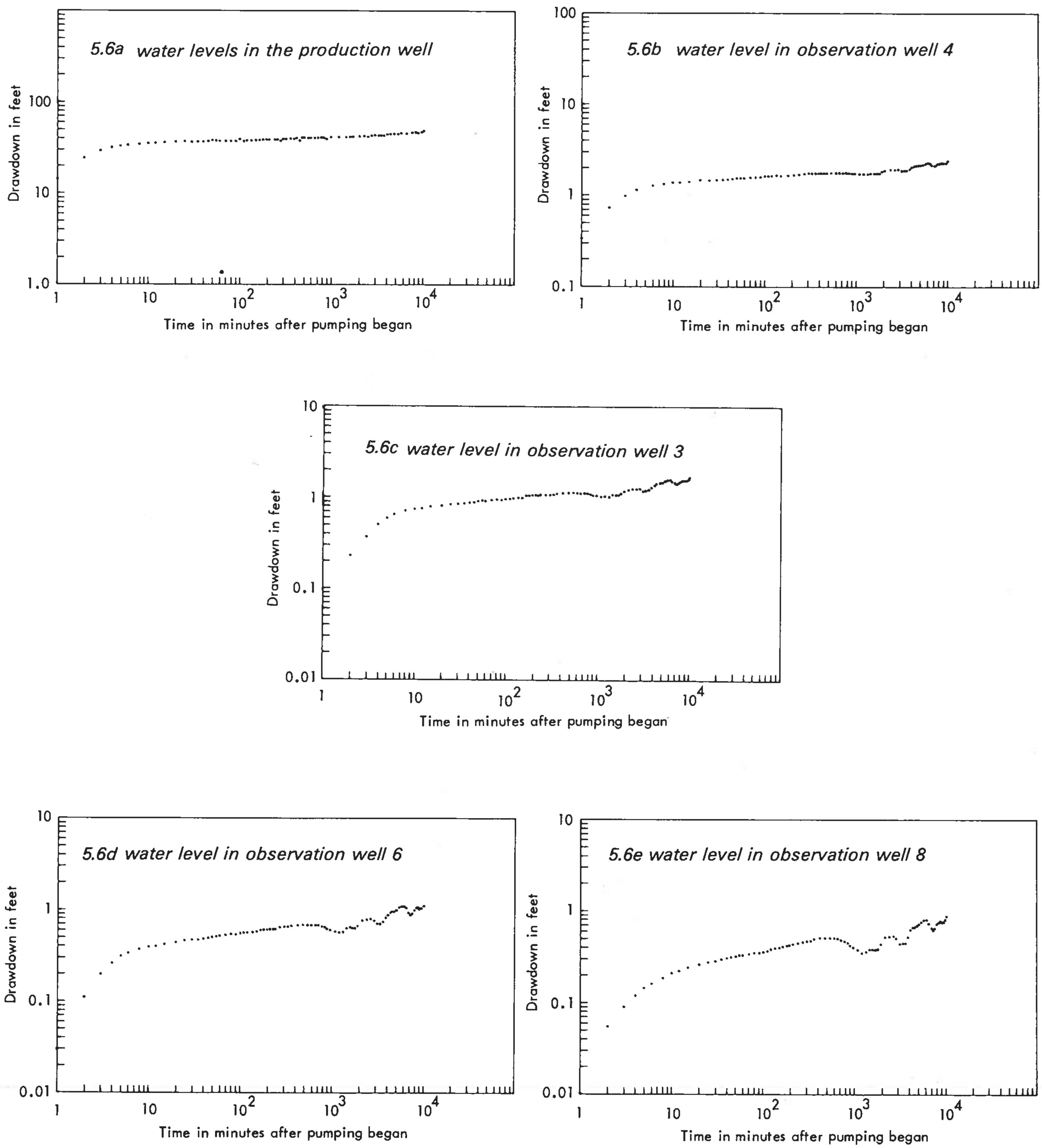


FIGURE 5.6 Time-drawdown graphs of observed wells

Table 5.2. Permeability Values Determined from Aquifer Performance Test Data

Length of test	Production rate (igpm)	Case	Observation well number	Distance from production well (ft)	Saturated thickness at end of test (ft)	K 2 igpd/ft
7 days (pumping well 5)	25	1	4	25	54.58	
			3	50	55.31	99
		2	3	50	55.31	
			6	100	55.90	120
		3	4	25	54.58	
			6	100	55.90	109
8 hours (pumping well 4)	33.3	1	5	25	54.62	
			6	125	56.32	130
		2	3	25	54.32	
			6	125	54.62	111

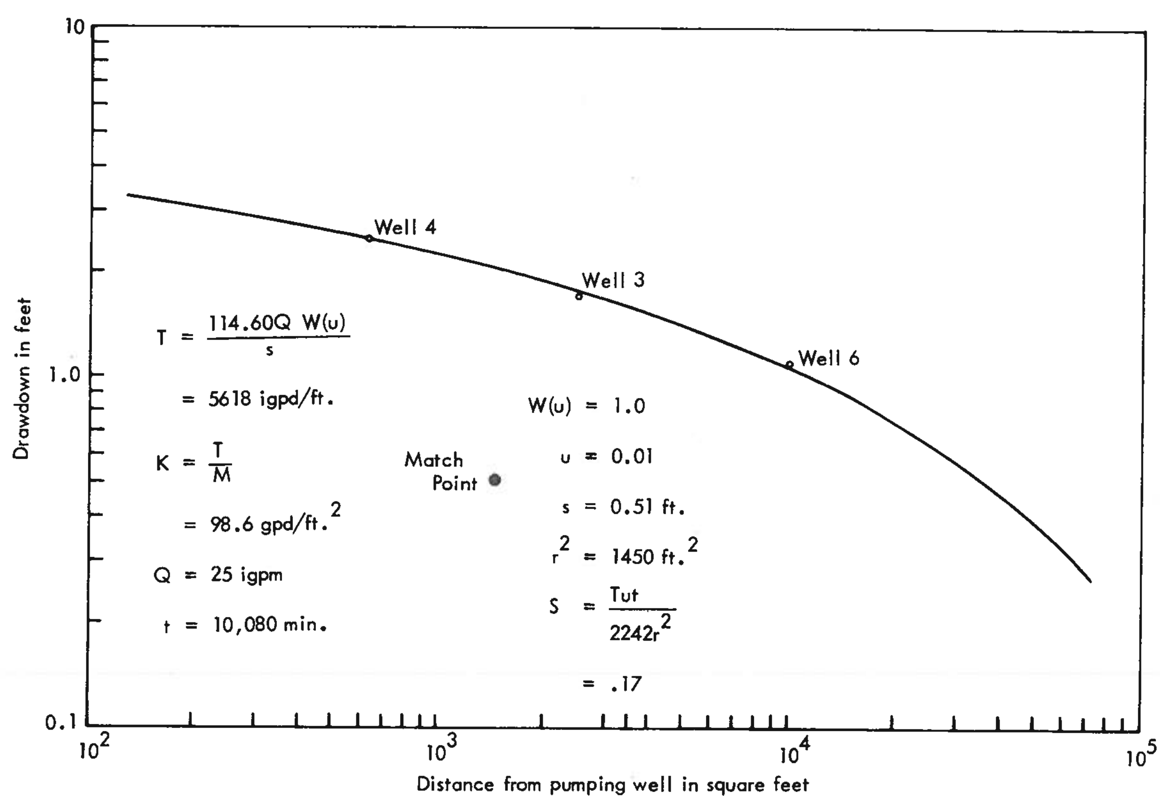


FIGURE 5.8 Distance-drawdown graph of water levels in wells after 1 week of pumping

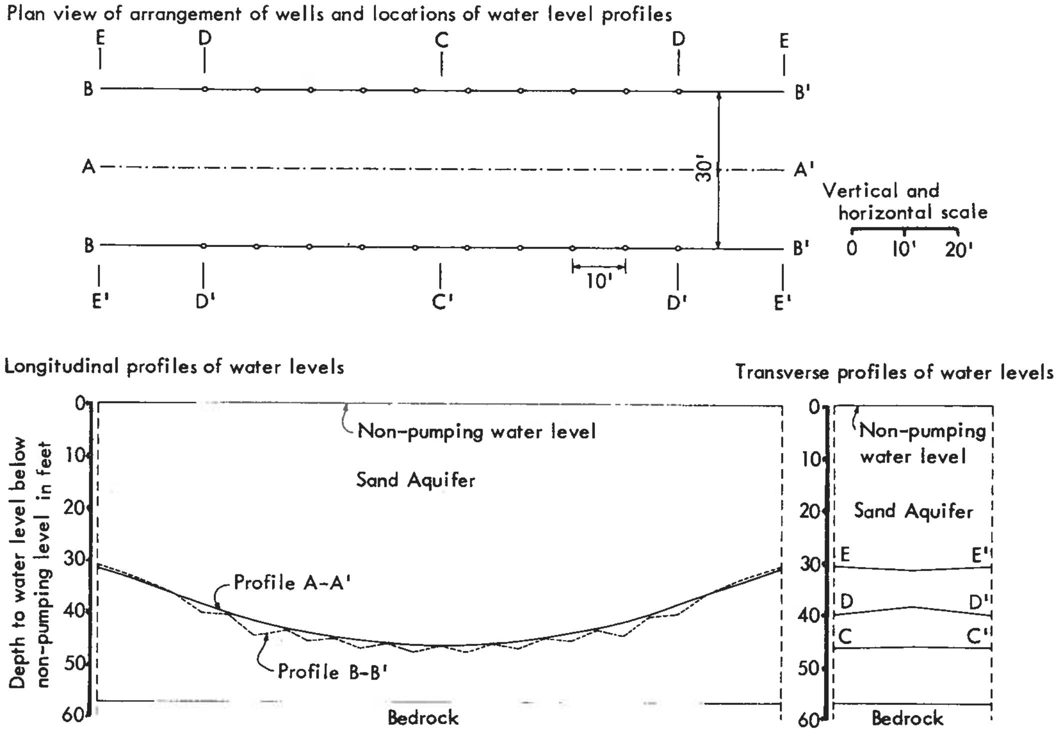


FIGURE 5.9 Details of dewatering scheme, trial 1
(Each well producing 25 igpm for one week)

mance tests and suggests that the poor performance of the 8⅝ in O.D. production well (5) can be related to conditions resulting from completion of the well. Assuming equilibrium conditions in the aquifer for the three close observation wells after 1 week of pumping, a determination of permeability can also be found graphically by means of matching a distance-drawdown curve to a type curve. The results of this determination are shown in figure 5.8. Conventional type curve solutions of transmissivity, the coefficient of storage, and permeability were not possible because the late time-drawdown data for observation wells could not be smoothed. Attempts to smooth the data by the application of corrections for barometric and partial penetration effects were unsuccessful.

Water levels in observation wells responded to pumping in a manner consistent with an unconfined aquifer. The average value of permeability calculated from basic data obtained from observation wells 3, 4 and 6 during the week-long test is 109 igpd/ft . The position of the water level in the production well after one week of pumping is shown in figure 5.1 but the corresponding theoretical calculation of drawdown in the aquifer for a point just outside the casing is 6.00 ft. Turbulent flow of water in the aquifer near the well and through the screen slots could explain the difference between the calculated water level and the actual pumping level. Recovery of water levels was almost complete in the vicinity of the production well minutes after pumping stopped.

PREDICTION OF WATER LEVELS IN RESPONSE TO PUMPING THREE DIFFERENT ARRANGEMENTS OF TWENTY WELLS

The position of the water level at any point in the sand aquifer overlying the tunnel after 1 week of pumping an arrangement of wells has been calculated by using equation 1 and the following constants: 1) the average value of K (109 gpd/ft) determined from the long performance test; 2) a constant pumping rate for each well of 25 igpm; and 3) the measured head in observation well 4 at the end of the aquifer performance test. The calculated average permeability is considered to be representative of the sands along the direction of the tunnel and therefore is reliable for prediction of water levels resulting from the pumping wells. Predicted water levels for three different arrangements of wells are shown in figures 5.9, 5.10 and 5.11. A single line of wells above the center line of the tunnel was not considered because of the probability of wells extending into the materials being excavated. Configuration of water levels for pumping rates greater than 25 igpm could not be calculated from the available information, although it is obvious that at rates greater than

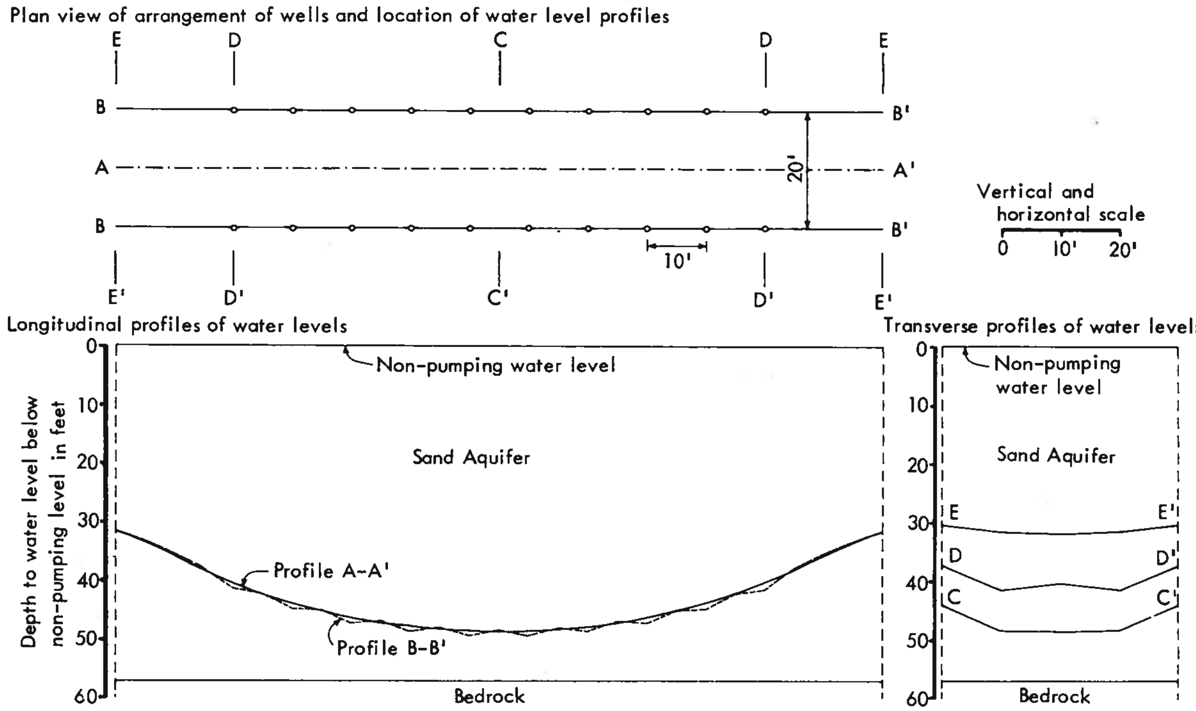


FIGURE 5.10 Details of dewatering scheme, trial 2
(Each well producing 25 igpm for one week)

25 igpm water levels will be lower for each of the three dewatering schemes shown. Several factors related to dewatering by the proposed well arrangements and in the manner described above can be noted.

1) The water level configuration in the area between the wells is relatively flat.
2) Extending the location of wells a distance of 20 ft behind the excavation face of the tunnel appears to be sufficient.
3) Spacing the rows of wells closer than 30 ft results in only slightly greater lowering of water levels between the wells.
4) Lowering of the water level to the bottom of the aquifer could be accomplished by increasing the pumping rate of each well or by spacing wells closer together in the rows.
5) Production of large amounts of water from a field of wells might result in the cone of depression intersecting known impermeable boundaries of the sand aquifer. This would have the effect of increasing the rate of drawdown during dewatering, and would therefore enhance any dewatering scheme using vertical wells.

CONCLUSIONS AND RECOMMENDATIONS

The investigation suggests that dewatering of the aquifer by vertical wells is physically feasible. An arrangement of wells as shown in figure 5.9 is the most suitable one to carry out a pilot dewatering scheme to evaluate the validity of the calculations resulting from the investigation. Effective well completions can be achieved with 4½ in O.D. steel casing finished with slots of 0.030 in width. Wells should be pumped at rates of at least 25 igpm or preferably at somewhat higher rates.

ACKNOWLEDGEMENTS

The cost of the investigation was borne by the City of Edmonton. The cooperation of Mr. T. Madunicky, engineer with the Water and Sanitation Department, was of great assistance to the author.

REFERENCES

Ahrens, T. P. (1957): Well design criteria; Reprint, Sept. and Nov., Water Well Journal, Urbana, Illinois, 8 pages.

Edward E. Johnson, Inc. (1966): Groundwater and Wells, p. 105-106.

Stalker, A. MacS (1968): Identification of Saskatchewan gravels and sands; Can. Journ. Earth Sci., Vol. 5, No. 1, p. 155-163.

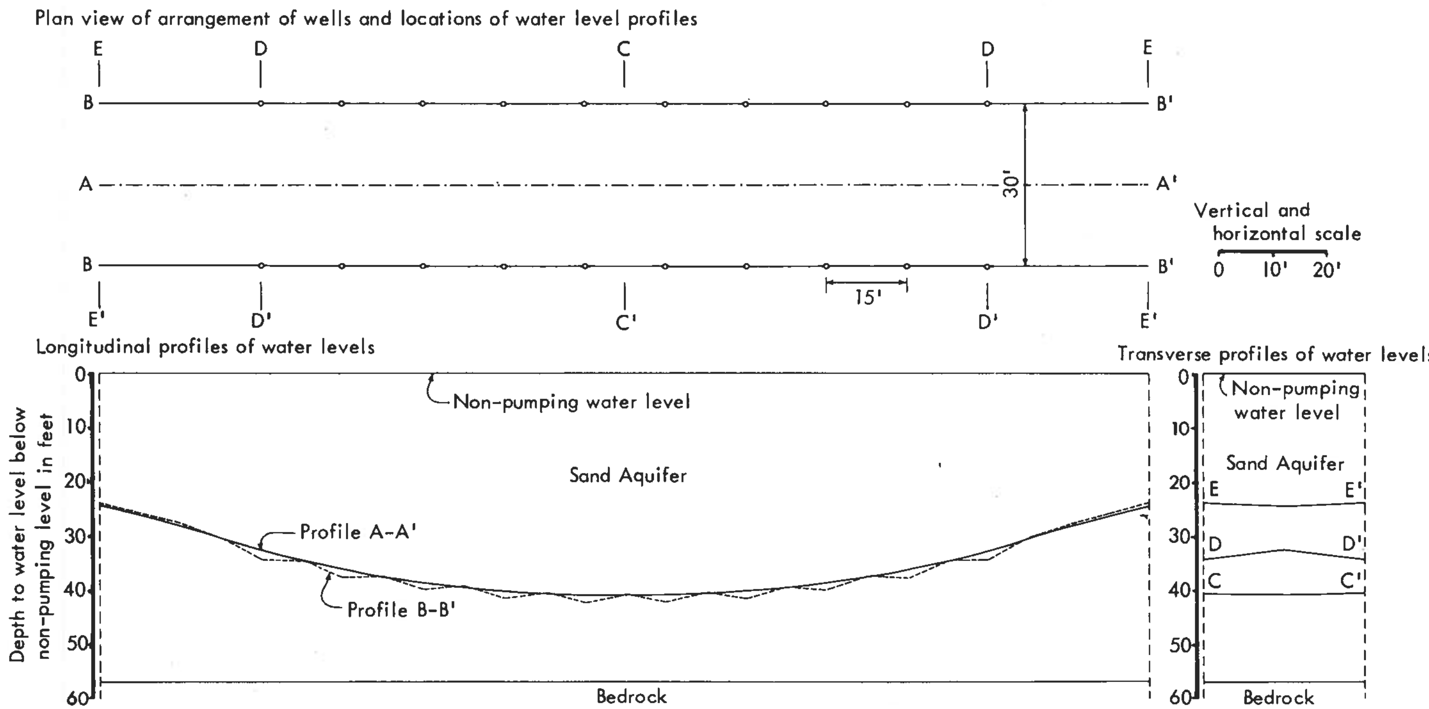


FIGURE 5.11 Details of dewatering scheme, trial 3

(Each well producing 25 igpm for one week)

TELEDELTOS MODELLING OF HOMOGENEOUS AND HETEROGENEOUS GROUNDWATER SYSTEMS

by R. Stein

ABSTRACT

Formal similarity between the laws governing flow of fluids in permeable media and electric currents allows subsurface fluid potential distributions to be modelled by electric analogy using a conductive medium such as Teledeltos paper. Such models can presently incorporate, to a certain extent, hydraulic conductivity variations both in direction and magnitude and play a useful role in the process of groundwater flow evaluation.

INTRODUCTION

Two-dimensional Teledeltos-paper analog models of groundwater flow have been actively used by the Groundwater Division of the Alberta Research Council since 1966. In 1963, Tóth (Tóth, 1968) began investigating the concept of modelling groundwater flow in vertical cross sections by applying a predetermined, continuously varying electrical potential along the upper boundary, this upper boundary being intended to simulate the water table. Tóth's application was successful but was restricted to homogeneous profiles; the author later developed modifications allowing conductivity variations to be incorporated. The modelling method has undergone a continuous process of evolution with respect to apparatus, instrumentation, and techniques; and, while there is much scope for still further advancement, it is felt that a description of the present state of development is warranted.

It is recognized that Teledeltos models cannot compete with the versatility and wide capabilities of the digital computer models nor is there any intention to do so. The latter have recently undergone such an accelerated rate of development that it is now possible to model virtually any conceivable hydrogeologic situation, both two- and three-dimensional. Variations in hydraulic conductivity and anisotropy are routinely incorporated and even unsaturated and saturated flow or decay from one to the other can be modelled (Freeze, 1972).

There do exist, however, situations in which Teledeltos analogs can serve a useful purpose and in the author's opinion further research to broaden and develop the method is warranted. A few such situations are described in the following paragraphs.

Teledeltos models can be used if and where computer facilities are not readily available. This means that hydrogeologists without access to computer facilities can still obtain the benefits from the application of the basic principles of flow system analysis.

A continous potential distribution is available from Teledeltos analogs; the investigator is not limited by the number or size of finite elements comprising the discretized models. Also, the results are directly measured and plotted as equipotential lines, making interpolation between discrete point values of potential unnecessary and allowing equipotential lines to be plotted at any desired density. As much detail as is desirable or necessary, anywhere in the model, and as the modelling progresses, is thus available.

The investigator experiences a valuable training process during the course of model construction. This is due both to the amount of detail which can be achieved and to the fact that each and every potential line is actually measured and produced by the investigator. His attention is forced on even the slightest inflection (which may not even be apparent from a potential distribution derived by extrapolation between discrete point values) or departure from the anticipated shape of an equipotential line or the expected nature of the potential distribution. The natural response to this is that he immediately looks for the cause and usually finds it to be some aspect of the configuration of the water table or of the geology, or both. Thus, the result of experience in model construction can be a "feeling" for cause-and-effect relationships between geology and topography and the resulting groundwater flow distribution that is difficult to achieve in any other manner.

ANALOG THEORY

The analogy between the laws governing groundwater flow in permeable media and the laws governing electric current has long been recognized and has been formally stated by numerous authors. It results from the fact that the Laplace equation can be arrived at either by considering the law of conservation of mass in conjunction with Darcy's Law or the conservation of energy in conjunction with Ohm's Law. For the sake of completeness, a brief summary is presented here.

For an element in a three-dimensional flow field Darcy's Law can be stated as

$$q_x = -K_x\frac{\partial h}{\partial x},\ q_y = -K_y\frac{\partial h}{\partial y},\ q_z = -K_z\frac{\partial h}{\partial z},$$

where:

x, y, and z are the three coordinate directions;

q_n = specific volume discharge (L/T);

K_n = hydraulic conductivity (L/T);

h = piezometric head = $\frac{p-p_o}{\rho g} + z$, (L);

p = fluid pressure (M/LT^2);

p_o = atmospheric pressure (M/LT^2);

ρ = fluid density (M/L^3); and

z = elevation above a standard datum (L).

The principle of conservation of mass requires that for steady flow and constant density

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} \quad \frac{\partial q_z}{\partial z} = 0,$$

and direct substitution of Darcy's Law into this equation yields

$$\frac{\partial}{\partial x}(K_x\frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_y\frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(K_z\frac{\partial h}{\partial z}) = 0.$$

For two-dimensional flow this simplifies to

$$\frac{\partial}{\partial x}(K_x\frac{\partial h}{\partial x}) + \frac{\partial}{\partial z}(K_z\frac{\partial h}{\partial z}) = 0,$$

and for the special case of porous media with homogeneous and isotropic hydraulic conductivity, further reduces to Laplace's Equation,

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial z^2} = 0.$$

Similarly, Ohm's Law can be stated as

$$j_x = -\sigma_x\frac{\partial V}{\partial x},\quad j_y = -\sigma_y\frac{\partial V}{\partial y},\quad j_z = -\sigma_z\frac{\partial V}{\partial z}$$

and the law of conservation of energy as

$$\frac{\partial j_x}{\partial x} + \frac{\partial j_y}{\partial y} + \frac{\partial j_z}{\partial z} = 0,$$

where:

j_n = current density (Q/L^2T);

σ_n = electric conductivity (TQ^2/ML^3); and

V = electric potential (ML^2/T^2Q).

Direct substitution yields

$$\frac{\partial}{\partial x}(\sigma_x\frac{\partial V}{\partial x}) + \frac{\partial}{\partial y}(\sigma_y\frac{\partial V}{\partial y}) + \frac{\partial}{\partial z}(\sigma_z\frac{\partial V}{\partial z}) = 0$$

which reduces to

$$\frac{\partial}{\partial x}(\sigma_x\frac{\partial V}{\partial x}) + \frac{\partial}{\partial z}(\sigma_z\frac{\partial V}{\partial z}) = 0$$

for current in a two-dimensional field with anisotropic conductivity. Further, for the special case of homogeneous and isotropic electrical conductivity this becomes Laplace's Equation,

$$\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial z^2} = 0.$$

It is apparent that analogous terms of the two systems are:

V and h,

σ and K, and

j and q,

and when one system is modelled by the other, proportionality between analogous terms must be retained.

Solution of the flow equations requires limiting the area under consideration and this is achieved by selecting the extent of the area so that mathematically correct boundary conditions an be applied. Such boundaries are basically of two types (Fig. 6.1):

1) Boundaries across which no flow can take place: these may be impermeable and geological in origin, or be situated under regionally significant ridges or depressions of topography. In either case, $\partial h/\partial n = 0$ at such a boundary. The electric analog to such boundaries is termination of the conductive medium which forces the condition $\partial V/\partial n = 0$ across the boundary.

2) Boundaries at which the head can be specified, either as a variable, or, in special cases as a constant, are generated by a free surface such as the water table. It follows that, since $p = p_o$ at the water table, the expression $h = (p-po/pg) + z$ reduces to $h = z$. Extensive areas of surface water in hydraulic connection with the subsurface represent the water table and under such conditions z simply becomes a constant. The electric analog to the specified head boundary is a boundary with the configuration of the water table along which the electric potential is made to vary in direct proportion to the elevation of the water table.

In summary, it is apparent that a hydraulic flow field can be modelled by an electrically conductive medium with the following properties:

1) a geometry which is similar to that of the hydraulic flow region;
2) an electric potential distribution on the upper surface which is everywhere directly proportional to the elevation of the water table;
3) boundary conditions with respect to the electric potential which are similar to those of the hydraulic flow region with respect to the fluid head; and
4) for heterogeneous or anisotropic conditions, an electrical conductivity distribution of similar geometry, and proportionally equal in direction and magnitude, to the hydraulic conductivity distribution in the hydraulic flow region.

MODEL CONSTRUCTION

Apparatus

The apparatus used in the construction of Teledeltos analogs of the two-dimensional, steady, fluid potential distribution which satisfies the above-mentioned conditions consists of the following:

1) A carbon-impregnated conductive paper of the trade name Teledeltos. Teledeltos is available in three types: L, M, and H, having rated resistivities of 1500 to 2000, 4000 to 10,000, and 8000 to 20,000 ohms per square of

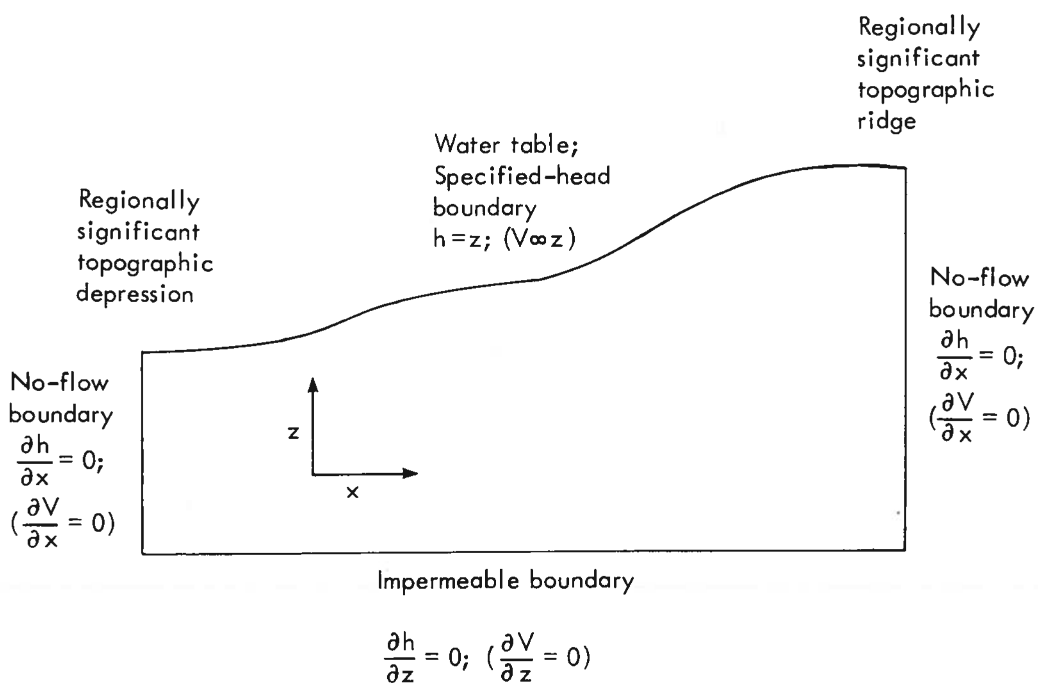


FIGURE 6.1 *Boundary conditions of a regional hydraulic flow field (electric flow field equivalents in brackets)*

random samples, respectively. One side of the Teledeltos paper is coated with a relatively non-conducting electrosensitive material of unspecified makeup and the other with a thin layer of lacquer. Type L is made especially for potential field plotting and the electrosensitive layer has been omitted.

With reference to type L Teledeltos paper the manufacturer specifies: "An individual sheet up to 30 inches square may, if sampled with concentric circle electrodes, show about plus or minus ten percent variation in resistance from the average over its area. Any square cut along and across the "grain" of the paper may show approximately ten percent difference in resistance across the width of the paper compared to that over the long dimension, the latter being the lesser (Western Union Telegraph Company, 1960)."

Resistivity is reported to be only slightly affected by temperature (about 0.2 percent per degree centigrade) but moisture content of Teledeltos apparently exerts a much larger effect. The manufacturers recommend that field mapping be completed during a period of uniform humidity and that moist hands be kept from contact with the paper.

2) A potential divider consisting of a number of sets of resistances connected in parallel. Each set consists of three series resistances (R_1, R_2, R_3), two of which (R_2 and R_3) are variable. The output is taken from R_3 and is connected to a plug-in type receptacle. The ground line is connected to four plug-in type receptacles (Fig. 6.2).

3) A regulated power supply with an output of between 0 and 10 volts dc at a current output between 0 and 10 amps. The load regulation of this power supply is ±1 percent or better.

4) A direct current, high impedance voltmeter capable of accurately measuring dc voltages from about 0.02 to 10,000 millivolts.

5) A conductive paint containing a concentration of pure silver sufficient to impart a volume resistivity of 0.002 ohm-cm.

6) A tracing probe consisting of a solid brass rod machined to the approximate shape of a sharpened pencil. The blunt end of the probe is connected to an input cable of the voltmeter while the sharp end is used to make contact on the conductive paper.

Construction Details

The line of vertical section along which the analog model is to be constructed is chosen so that its two end points coincide with either major topographic ridges or depressions. The trend of the section should be taken as nearly as possible parallel with the general slope of the land surface, or the water table if it is known to be different. Unless the model is intended to include an overall

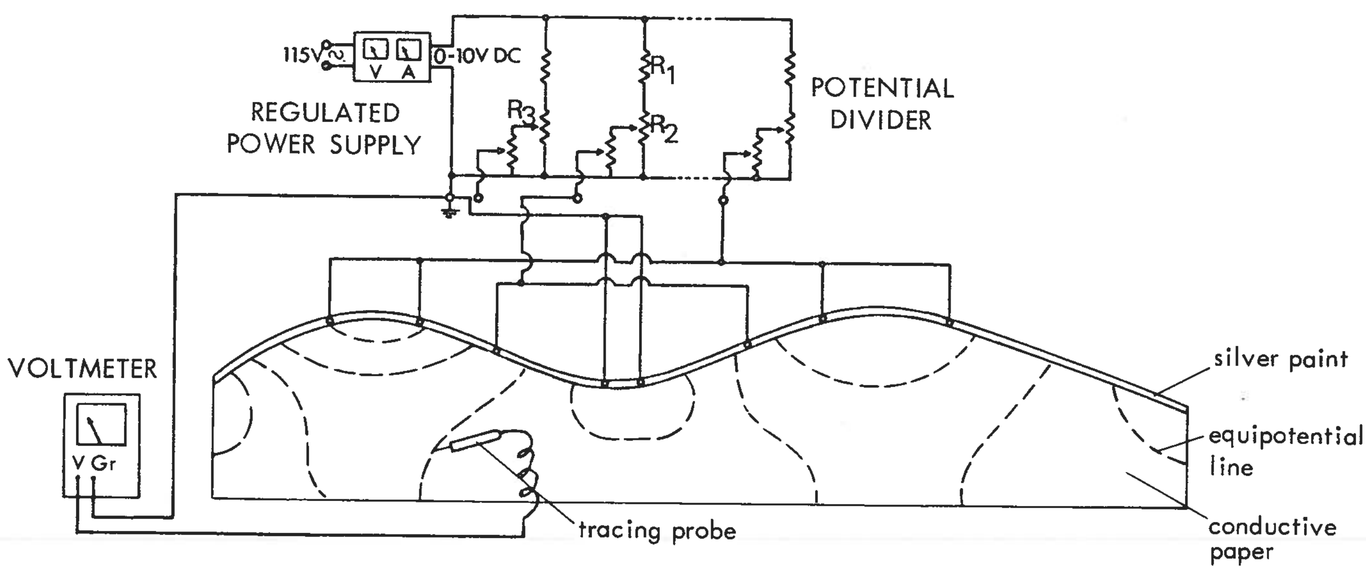


FIGURE 6.2 Schematic diagram showing apparatus hook-up

anisotropy with respect to hydraulic conductivity, a topographical cross section is constructed to an appropriate working scale without vertical exaggeration. The topographic surface of the cross section (or more correctly the water table configuration, if it is known, and especially if it is known not to conform to the topographic surface) is then taken to be the upper boundary of the model (Fig. 6.2).

The lower boundary is chosen where geologic evidence shows that a major decrease in hydraulic conductivity exists below the boundary, and is modelled as an impermeable boundary. The end points of the topographic profile and the lower boundary are usually joined by vertical lines to form the two end, or no-flow boundaries.

A cross section of the same geometry and size as just described, but with about 2 mm greater depth is cut from the Teledeltos paper. Because of the slight anisotropy of the Teledeltos paper, the long direction or "grain" of the paper is usually positioned so as to be parallel to known bedding plane or other direction of known or anticipated anisotropy. The extra 2 mm depth is allocated to the top boundary of the Teledeltos model and is painted as evenly as possible with silver paint in order to allow the electrical potential which will be applied later to distribute itself evenly along the boundary.

Each electrode is constructed simply by soldering a 20-gauge insulated copper wire to the top of a steel pin. The steel pins are inserted into the 2-mm strip of silver paint at points where topographic contours of predetermined intervals touch or cross the line of section, and a small amount of silver paint is applied to the junction to insure a secure connection. Where a specific contour elevation occurs more than once along the line of section, all electrodes inserted at that elevation are joined together by the copper wire to form a multiple electrode. This procedure, however, should not be overdone since later potential adjustments to the upper boundary will become difficult to execute properly if the electrode configuration is very complex. It is advantageous to select and space electrodes so that their configuration is as simple as possible and to minimize both the number and size of multiple electrodes.

Each single or multiple electrode is then connected to a different set of variable resistances of the potential divider. In this manner, each set of variable resistances is connected to a specific elevation and it is therefore possible to adjust or vary the electrical potential or voltage at each specific elevation by adjusting the appropriate set of variable resistances.

The adjustments are made in such a way that the electrical potential values along the top boundary of the conductive paper vary proportionally to the water table values of the cross section. The lowest elevation value is assigned a zero electrical potential and its electrode is connected to a ground receptacle in the potential divider. The ground cable of the voltmeter is connected to this electrode and subsequent adjustments are made by reading the potential difference (in millivolts) between the zero electrode and the electrode which is being adjusted.

Each electrode must be adjusted several times since each adjustment affects several adjacent electrodes; an iterative procedure is therefore used. All electrodes are first adjusted roughly (to within ± 10 percent of their desired value) and then to a successively finer degree until the electrical potentials are within ± 1 percent or better of their desired values. The end product of this procedure is an electrical potential distribution along the top boundary of the Teledeltos paper which is to within ± 1 percent proportional to its elevation distribution.

Potential Distribution

After the potentials have been set along the top boundary of the model, the potential distribution within the flow region is mapped. The procedure simply consists of tracing lines on the Teledeltos model along which the electrical potential is constant. To achieve this the ground cable of the voltmeter is connected to the zero electrode and the voltage input cable of the voltmeter is connected to the tracing probe. Equipotential lines are then mapped by moving the tracing probe over the Teledeltos paper while maintaining a constant reading on the voltmeter, this reading indicating the potential difference between the zero electrode and the tracing probe along the equipotential line being mapped. Lines are constructed at regular intervals of potential difference until a sufficiently detailed picture of their distribution is obtained.

If the model is very large and complex, tracing time may be in the order of one day or more. Under such conditions it is not uncommon to experience instrumental drift which manifests itself in undesirable changes to the potential distribution along the upper boundary and within the model. In order to overcome such difficulties, two procedures are followed. One is to keep the power supply and potential divider well ventilated and thus at relatively constant temperature. The other is to set the potentials at the upper boundary as accurately and reproducibly as possible to allow frequent checking and resetting as required.

Accuracy and reproducibility of potentials at the upper boundary are important for another reason. Potential gradients throughout the model vary, and in some areas (areas of high conductivity, stagnant zones at junctions of flow systems, and junctions of vertical and horizontal impermeable boundaries) may become extremely low. In such instances it will be impossible to accurately measure minute changes in potential difference if the difference between the ground, or reference, electrode and the particular potential line being traced is high. It therefore becomes necessary to use as a reference electrode one which is close in absolute value to the potential in the low-gradient area. In this way it is possible to use a scale of higher sensitivity on the voltmeter and thus achieve any desired degree of detail in any area of the model.

MODELLING HYDRAULIC CONDUCTIVITY VARIATIONS

Bonded Teledeltos Layers

The method which so far has yielded good results with respect to modification of the models in order to achieve variations in conductivities is that of simply joining two or more (to a practical maximum of five) sheets of Teledeltos together. Since, as already mentioned, Teledeltos paper is presently available with resistivities of 1500-2200 /sq, 4000-10,000 /sq, and 8000-20,000 /sq, it is conceivably possible to obtain virtually any conductivity ratio between one and about 50:1 simply by joining appropriate numbers of two or more papers together. It is, of course, necessary first to measure accurately the conductivities of papers to be used and select the proper combinations accordingly.

The bonding procedure is simple. First, the area to be modified is outlined and the appropriate shape is cut from the paper that has been selected to be added. The top surface of the background paper and the bottom surface of the paper to be added are cleaned by wiping them with tissue paper soaked in acetone. The bottom surface of the modifying paper is then sprayed lightly and evenly with an aerosol plastic compound (such as that used in "fixing" letraset characters in drafting procedures) and placed in position. The paper is then held firmly in its final position with one hand while tissue paper, moderately soaked in acetone, is pressed down and pulled along slowly over the entire layered area. As the acetone-soaked tissue paper is moved slowly along, the other hand can be used to apply pressure just behind the tissue paper where the acetone is evaporating from the Teledeltos papers. Should any portion of the papers be not completely bonded, the area can be resoaked and pressure applied until the situation is corrected.

Successive layers are added simply by repeating the procedure described. If only two layers are to be joined, the Teledeltos papers need neither be cleaned nor sprayed with plastic; their lacquer-coated sides are simply placed back to back and the acetone pressure technique is applied.

While it may seem paradoxical that an insulating compound such as acrylic plastic can be used to provide an electrically conductive bond between two conducting sheets, the method does work. It is thought that the acetone dissolves the plastic layer at the boundary between the two sheets of Teledeltos, redistributes it into both sheets, and leaves a very small amount at the boundary to provide the bond. Conducting characteristics of the Teledeltos are not altered since no electrically conducting material is added and physical contact between carbon particles in the paper is maintained by keeping the total amount of plastic relatively low. A surprisingly large amount of plastic will still allow such particle contact to be maintained.

Silver Paint-Carbon Black Mixtures

A second method of modelling hydraulic conductivity variations has been developed in an attempt to provide ratios higher than those possible with presently available Teledeltos paper combinations. This method, however, has several inherent drawbacks which make it difficult to use and which present accuracy restrictions severe enough to question its quantitative value.

The method consists of spreading a thin, even layer of conductive paint on the desired area of the Teledeltos model. Carbon black is thoroughly mixed with silver paint in proportions sufficient to produce the desired conductivity. Depending on the relative amount of carbon black added, a thinner such a xylene (or as recommended by the paint manufacturer) and sometimes a small amount of plastic binder must be added to the mixture in order to maintain proper viscous and cohesive properties.

To control the thickness of the paint layer it is applied simultaneously with a layer of NP40 silk screen on which the desired shape of the high conductivity area has been masked with an appropriate pressure sensitive tape. The masked area is positioned over the Teledeltos paper and the paint applied. Both the paint and silk screen are then pressed to the Teledeltos paper (fingers work well) until the paint dries sufficiently to hold the combination to the paper. Excess paint is then scraped flush to the silk screen and excess screen is carefully trimmed away with a sharp scalpel.

The accuracy of the system is rather low. Under ideal conditions, test strips can be constructed with less than ±10 percent variation in conductivity. However, in actual model construction shape and size factors will limit accuracy and reproducibility to about ±25 percent. Small, evenly proportioned areas of very high conductivities (1000 or more times that of Teledeltos) are best suited to this method.*

Anisotropy

Modelling of hydraulic situations with anisotropic conductivities is possible for certain geological configurations by following the procedures of conformal transformation as outlined by Maasland (1957). Maasland shows that any hydraulic system, either layered or unlayered, and with anisotropic hydraulic conductivities, can be represented by an equivalent isotropic system by suitably expanding or contracting dimensions in directions coincident with

*For an example of a Teledeltos analog model which uses both methods of varying conductivities to simulate a complex geological situation the reader is referred to Gabert (1974).

principal hydraulic conductivity directions. Such an equivalent system contains a further inherent advantage: the quantification of a model with respect to net flow through the model is greatly simplified since flow lines can be constructed orthogonally to equipotential lines.

Geometric manipulations necessary in performing the transformation, however, limit transformable situations to those in which areas of differing anisotropy (either in degree or in orientation of principal conductivity directions) are separated by boundaries consisting of straight lines extending from one external model boundary to another.

For two-dimensional flow problems such as those solved by Teledeltos analogs, Maasland shows the factor used in expansion or contraction of dimensions to be equal to $(K_h/K_v)^{1/2}$ and the conductivity, K, of the equivalent isotropic system to be $(K_h K_v)^{1/2}$, where K_h and K_v are conductivities in the x and z directions, respectively, and are chosen to be coincident with the principal directions of anisotropy.

It will be recalled that the conductivity of Teledeltos paper is usually larger along than across its machining direction and that the magnitude of this difference may be as high as 1.5:1. If a significant degree of anistropy is found to exist in the Teledeltos paper to be used in a transposed model, it may be necessary to contract the model by a further factor (σ_x/σ_z), where σ_x and σ_z are conductivities of the Teledeltos along and across the machining grain respectively.

The major problem concerning anistropy with respect to hydraulic conductivity in Alberta is not whether solutions for any conceivable configuration of anisotropy can be obtained, but rather that the quality of anisotropy itself has never been measured or determined in the field. It does seem reasonable, however, that hydraulic conductivities parallel to bedding should be from 10 to 100 times those perpendicular to bedding, at least in these portions of the province underlain by Mesozoic sediments.

Quaternary deposits, and especially glacial till, are another matter. Controversy still exists as to whether vertical hydraulic conductivities are larger than horizontal conductivities due to the characteristically vertically oriented fractures usually observed in till outcrops. The question as to whether such fractures exist at depth is fundamental but remains unanswered at the present time. The author's own feeling is that they do not exist in saturated till and that bulk hydraulic conductivities are probably not greater in the vertical direction.

Until the above questions are answered quantitatively, it seems reasonably valid to use overall vertical exaggerations from $\sqrt{10}$ to 10 to represent greater horizontal hydraulic conductivity in Teledeltos models.

SAMPLE TELEDELTOS MODEL

In order to verify the correctness and hence the usability of the Teledeltos bonding technique, a simple analog model was constructed and compared to a finite element model of the same hydrogeological situation (Fig. 6.3). The Teledeltos model used the high resistivity Teledeltos (type H) as its base and modifications were introduced by bonding one layer of type H, one layer of type L, and three layers of type L Teledeltos to areas, 1, 2, and 3 of the model, respectively.

After the model was constructed, resistivities of both papers were measured along and across the paper "grain" on samples taken from areas of the Teledeltos rolls within 3 feet of the model components. Samples were trimmed to a width of 1 cm and a length of about 20 cm, the resistance across the total length of the long direction measured, and this value divided by the strip length to yield paper resistivities in ohms/square. Average resistivity values were found to be 1300 and 7300 ohms/square along the paper grain for type L and H papers, respectively, while resistivities across the paper grain were measured to be from 1.1 to 1.4 times those along the grain. Variations in the resistivity along the grain were in the order of ±6 percent of their average value.

Using average values of measured resistivities, the calculated conductivity ratio of type H to type L paper was 7300:1300 or 5.6:1. The anticipated conductivity ratios of the modified model areas were therefore 2:1 for area 1, (1 + 5.6) or 6.6:1 for area 2, and 1 + 3(5.6) or 17.8:1 for area 3 in the direction along the paper grain. Conductivity ratios across the grain were, of course, subject to the previously mentioned measured values of anisotropy.

A finite element numerical model was set up using these average conductivity ratios and both extremes of the measured anisotropy values. Comparison of these models with the Teledeltos model showed variations in potentials of up to ±5 percent of the total potential drop across the models and it was decided to cut the Teledeltos model in such a manner that the actual resistivities both along and across the grain could be measured.

These values were found to vary slightly by more than ±5 percent from the previously measured average values but were well within the Teledeltos manufacturer's specifications of ±10 percent of average. A significant and unexpectedly high, local variation in resistivity across the type H paper grain was, however, discovered to exist in the right one third of the Teledeltos model. The conductivity ratios calculated from these resistivity values are given in figure 6.3 and when substituted into the finite element model, agreement with the potential distribution of the Teledeltos model was well within ±1 percent of the total potential drop across the model.

From a comparison of the Teledeltos and finite element models it can be concluded that the method of bonding Teledeltos papers as discussed in this paper is valid and introduces no significant errors. However, resistivity variations in Teledeltos paper, both along and especially across the grain are significant and must be carefully accounted for. The author suggests that Teledeltos immediately adjacent to a proposed model be sampled and measured and if resistivity values vary beyond acceptable limits the model should be chosen from a different portion of the Teledeltos roll. Similarily, any Teledeltos used for modifying conductivities should be carefully chosen on the basis of acceptable resistivity variations.

ACKNOWLEDGMENTS

R. Bibby set up the computer models used in evaluating the Teledeltos bonding technique and provided much valuable discussion and many helpful suggestions with respect to the contents of this paper. R. Bibby, J. Tóth, and R. I. Vogwill critically read the paper and Mrs. D. Borneuf typed the manuscript. Their help is gratefully acknowledged.

REFERENCES

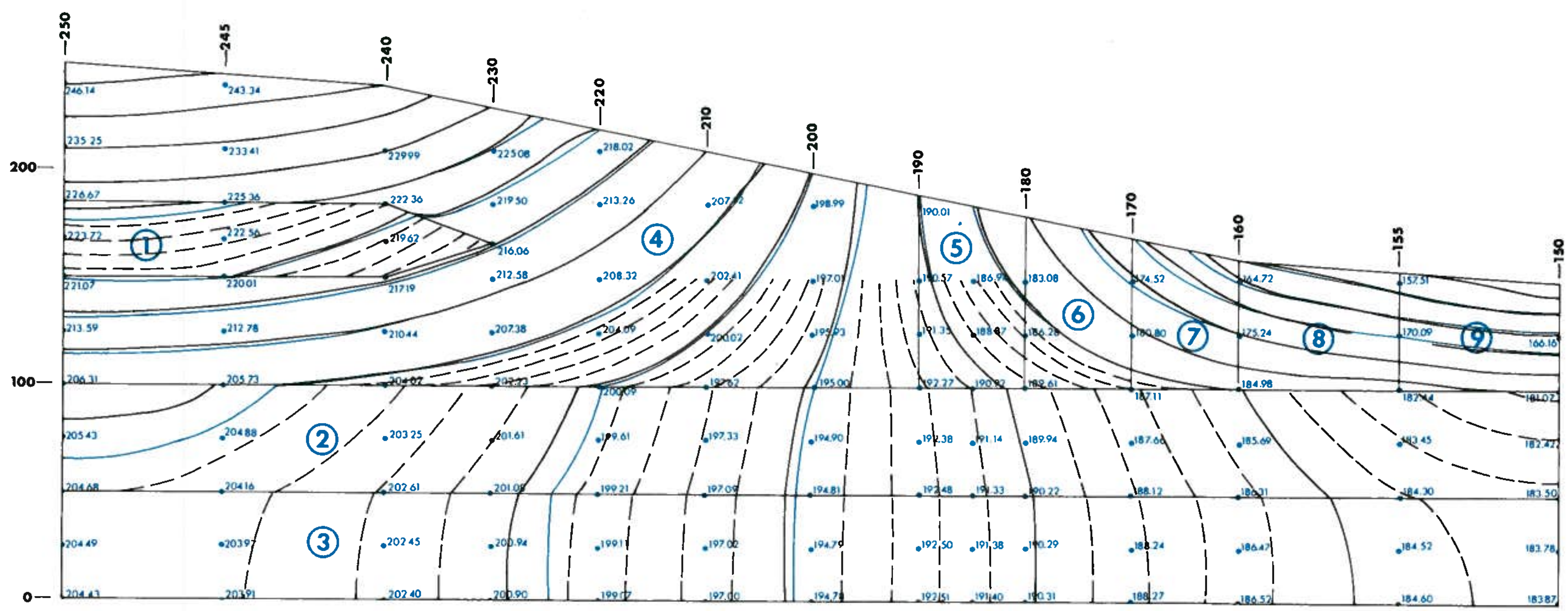
Freeze, R. A. (1972): Subsurface hydrology at waste disposal sites; IBM J. Res. Develop., March 1972, p. 117-129.

Gabert, G. M. (1974): Hydrogeology of Red Deer and vicinity, Aberta; Alberta Res. Coun. Bull. 31, 100 pages.

Maasland, M. (1957): Soil anisotropy and land drainage; *in* Luthin, James N., editor, Drainage of Agricultural Lands; Amer. Soc. Agron., publisher; Madison, Wisconsin, 1957, p. 216-240.

Tóth, J. (1968): A hydrogeological study of the Three Hills area, Alberta; Res. Coun. Alberta Bull. 24, 117 pages.

Western Union Telegraph Company (1960): Analog field mapping on "Teledeltos" recording paper, 3 pages.



LEGEND: equipotential lines determined by Teledeltos analog

equipotential lines determined by Finite Element model

•199.61 position and magnitude of computer determined potential value

PERMEABILITY RATIOS: Areas annotated ① ②, and ③ are laminated Teledeltos paper. Areas ④ to ⑨ are measured conductivity variations in unmodified Teledeltos paper. The horizontal and vertical permeability ratio respectively for each area is: ① 2.0, 1.8; ② 7.6, 6.8; ③ 20, 18; ④ 1.0, 0.9; ⑤ 1.0, 0.8; ⑥ 1.0, 0.7; ⑦ 1.0, 0.6; ⑧ 1.0, 0.5; ⑨ 1.0, 0.7.

FIGURE 6.3 Potential distribution for a hydraulic cross section modelled by Teledeltos and finite element computer models

DLSPLOT: A COMPUTER PROGRAM FOR TRANSLATING DOMINION LAND SURVEY COORDINATES TO UNIVERSAL TRANSVERSE MERCATOR COMPATIBLE COORDINATES

by A. T. Lytviak

ABSTRACT

The computerization of many phases in the production of the reconnaissance hydrogeological map series has encountered difficulties inherent to mapping in a complex coordinate system. The National Topographic System, using Transverse Mercator projections, has polar coordinates. The Dominion Land Survey system is a synthesis of orthogonal and polar coordinate systems. The computer output device operates in an orthogonal system. If Dominion Land Survey coordinates are used as input and National Topographic System compatible maps are desired as output, mapping by computer must invoke a suitable translation program. The construction of such a program was undertaken by simplifying the coordinate system to a maximum extent consistent with keeping the resultant errors within set limits. The scale of 1:250,000 was used as a criterion for acceptability, as this scale is most commonly used in the reconnaissance map series. Simplicity of utilization was achieved by minimizing the parameters necessary to define the area to be plotted. Three parameters were found necessary and additional ones useful. These parameters were: horizontal field in ranges, the vertical field in townships the scale as a ratio, and two adjustment factors.

INTRODUCTION

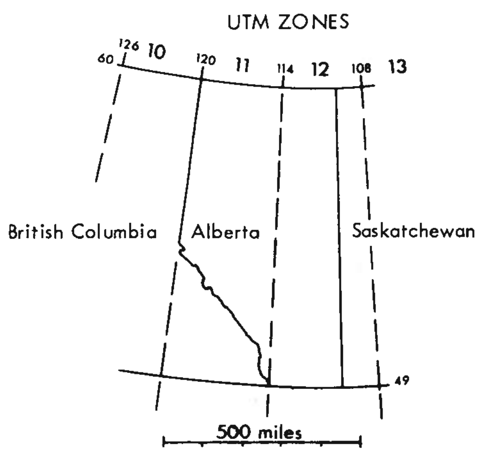
DLSPLOT is a computer program constructed to make it possible to plot geographic data by machine. The basic difficulty is that such data are located in the Dominion Land Survey (DLS) system and have to be plotted in the Universal Transverse Mercator (UTM) system. The goal was to develop a generalized program that would demand only a minimal knowledge of computer programming language and a basic understanding of the DLS coordinate system to produce acceptable plots of data. Acceptability of the plots was to be judged on the basis of fit to a National Topographic System 1:250,000 scale map.

In constructing such a program three coordinate systems must be considered: the terrestrial system of degrees latitude and longitude; the DLS system of meridians, townships, ranges, sections, quarter sections, and legal subdivisions; and the machine coordinates of inches vertically and horizontally. Of these only the last is orthogonal on a plane. The first is orthogonal on a sphere but suffers from distortion of direction or scale or both when represented on a plane surface.

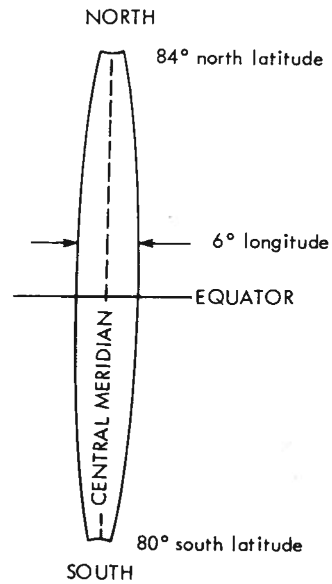
THE COORDINATE SYSTEMS

The National Topographic System uses a UTM projection. This projection may be visualized in the following manner. The sphere of the earth is cut by planes passing through its axis into 60 segments, each 6 degrees of longitude wide. On the sphere's surface each plane forms a great circle through the earth's poles. When the surface of one such segment is laid on a plane and contracted and expanded as necessary so that it is flat, this forms a UTM zone (Fig. 7.1a). The province of Alberta is contained within two such zones (Fig. 7.1b). Each zone in turn is subdivided into map sheets, the geometry and distortions of which are self-consistent within each zone. In Alberta the map sheets are 2 degrees of longitude wide and 1 degree latitude high (Fig. 7.2).

The DLS system is a roughly plane orthogonal grid laid out on the earth's surface primarily for legal land holding description. This coordinate system is the most commonly used system in the province for specifying geographic locations. As a result, most hydrogeological data are located in DLS coordinates. In Alberta the land locations are referenced to the fourth, fifth or sixth meridians, which are



7.1a Shape of a UTM zone relative to the province



7.1b Shape of a UTM zone

FIGURE 7.1 UTM zones

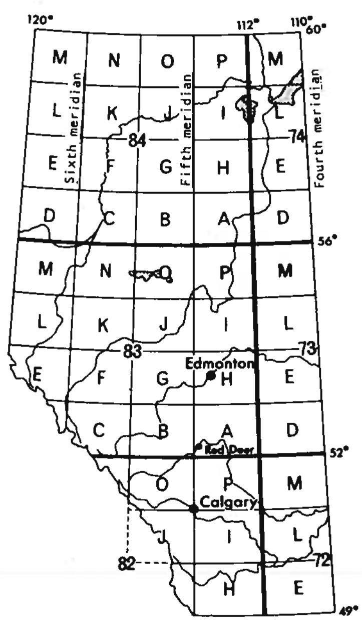


FIGURE 7.2 Map of Alberta showing NTS divisions

north-south running reference lines (Fig. 7.2). Between the meridians are 6-mile wide, north-south running strips known as ranges. Ranges are numbered westward from each meridian. As well, the province is divided into 6-mile wide strips which run east-west. These, known as townships, are numbered northwards starting at the 49th parallel of latitude. Each 6-mile by 6-mile grid thus laid out is also, confusingly, called a township and is subdivided into 36 1-mile by 1-mile squares. These, known as sections, are numbered sinusoidally starting in the bottom right-hand corner. That is, the bottom row is numbered right to left, the one above it is numbered left to right and so on until section 36 is reached in the upper right-hand corner (Fig. 7.3). The sections are further subdivided into one-half mile squares producing four quarters or into 16 one-quarter mile squares known as legal subdivisions. Legal subdivisions are also numbered sinusoidally from the bottom right-hand corner.

Thus in Alberta a land location or description usually consists of giving a meridian, a township, a range, a section and a quarter section or a legal subdivision.

SIMPLIFICATION OF THE UTM PROJECTION

It is quickly apparent that the geometry of a UTM projection is relatively complex, as both lines of latitude and longitude are represented as curved lines. On actual map sheets, the lines of longitude very nearly approximate straight lines. In fact, along the edge of a UTM zone, between the latitudes of

50 and 51 degrees, the separation of the curve and a straight line is only 1.8 metres.* In the context of reconnaissance mapping, on scales of 1:125,000 to 1:500,000, this is negligible. Discounting this curvature, one is left with a projection which appears to closely approximate an axial conic projection. (That is, a projection of the earth's surface on to a cone coaxial with the earth's geographic axis.)

Using the curvature of lines of latitude and the convergence of the lines of longitude, it was calculated that the apex (point C in Fig. 7.4a, 4b) of the cone of projection would be about 3090 miles north of the 49th parallel of latitude. This distance is measured on the surface of the developed, unrolled cone. The standard parallel, the latitude at which the horizontal scale is true, was arranged to run through the center of the map sheet to be plotted. All east-west lines on such a projection are represented by arcs of constant radius and north-south lines by radii of the developed cone. This "projection" is, strictly speaking, not a projection, because points F and E, if center-projected onto the cone, would project as points f and e (Fig. 7.4a); in fact, the distance between points A and B (Fig. 7.4b) which represent F and E (Fig. 7.4a) is made equal to the arc distance between F and E. Thus the north-south scale remains constant throughout the developed cone. The east-west scale increases away

* Personal correspondence with L. M. Sebert, Head, Mapping Program Section, Topographical Survey Directorate.

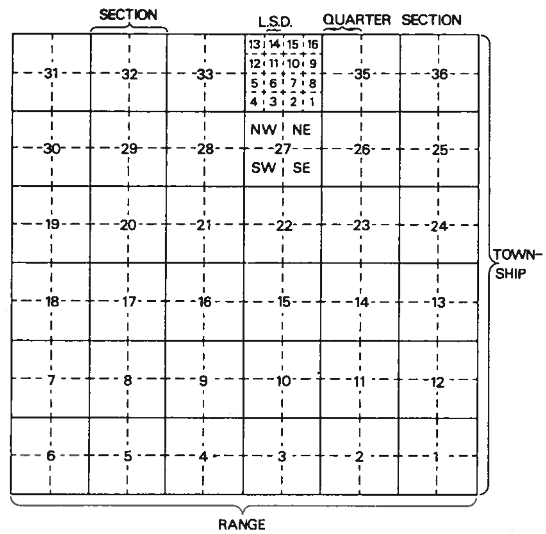


FIGURE 7.3 Subdivision of a township

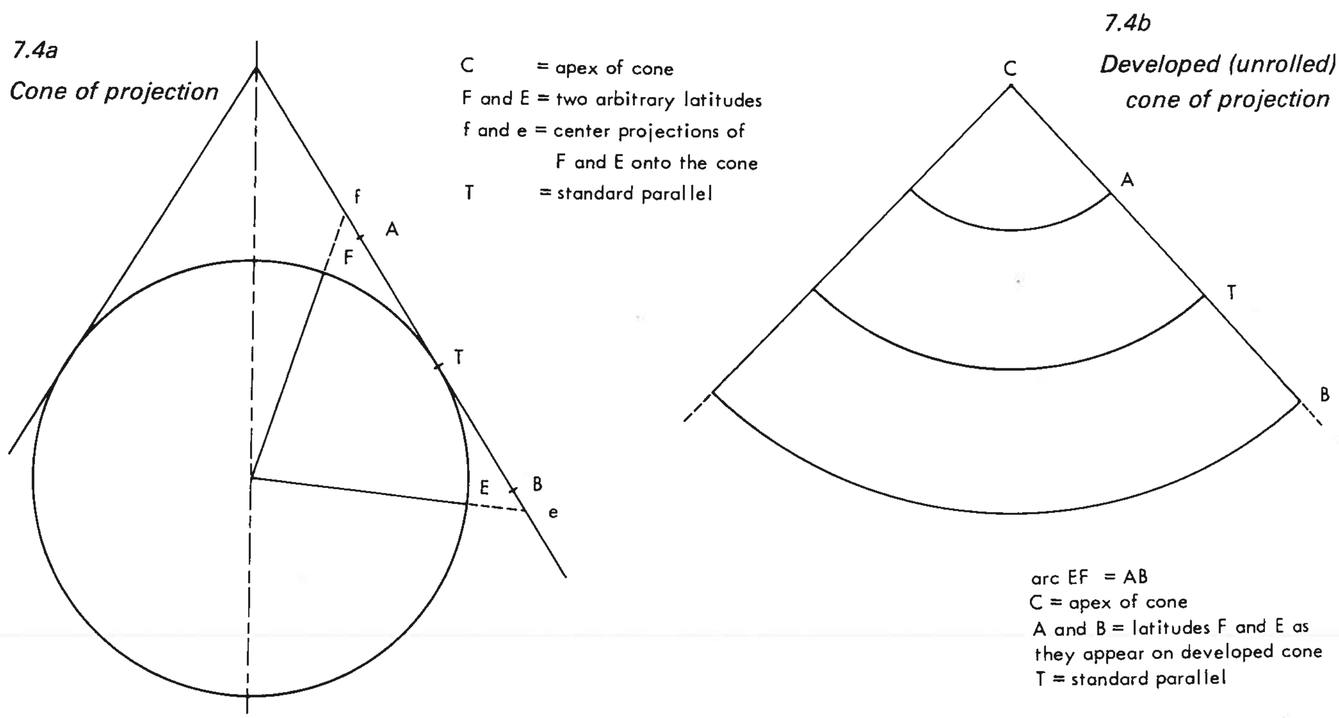


FIGURE 7.4 Cone of projection and unrolled cone of projection

from the standard parallels as a function of the divergence of the radii of the cone and the sphere at a given latitude. This function was approximated by increasing horizontal scale as a function of the sphere and decreasing it as a function of the cone in such a way that true scale was achieved at the center of the map sheet to be plotted. This was tested and found adequate in map sheets up to 30 townships wide.

A difficulty arises in the laying out of the north-south running range lines. The fourth, fifth and sixth meridians coincide with the lines of longitude of 110, 114 and 118 degrees, respectively. Due to the decreasing circumference of the earth at increasing latitudes, any lines of constant longitude converge poleward. Range lines are referred initially to a meridian, then stepped off in 6-mile strips westward. If this had been done without adjustments of some sort, the range lines, excepting the meridian, would have diverged increasingly from the lines of longitude westward and northward. The difficulty was overcome by establishing east-west reference lines called baselines. The 49th parallel of latitude was chosen as the first baseline. Subsequent baselines were laid out at 24-mile intervals northwards. The strips between baselines were subdivided into four 6-mile strips, thus the first, fifth and every subsequent four townships are bordered on the south by a baseline.

Each baseline is subdivided into 6-mile segments starting at a meridian and going west to the next meridian. North-south lines of constant longitude are then passed through these 6-mile divisions to establish ranges. Each such range line extends 12 miles (two townships) south and north of the baseline. The range lines projected from adjacent baselines meet halfway in an offset known as a correction line. This offset results from the laying of this approximately plane-orthogonal grid on a spherical surface while keeping orientations sphere-orthogonal (Fig. 7.5). The amount of offset can be calculated as a cosine function of latitude (Fig. 7.6) and in the program it is handled as such, eliminating the need to specify the magnitude and location of each correction.

CALCULATION OF PLOTTING COORDINATES

In the program all the coordinates are initially considered as orthogonal and are referenced to the meridian, which is considered vertical, and to the horizontal center line of the plot. DLS coordinates are converted to miles west of the meridian and miles north and south of the horizontal reference line. This treatment produces an orthogonal grid of the township and range lines (Fig. 7.7a). To produce offsets analogous to correction lines, the horizontal coordinates are then multiplied by the cosine function previously mentioned, a procedure taking several steps. Firstly, each horizontal strip of 24 miles is multiplied by the factor which corresponds to the latitude of the baseline

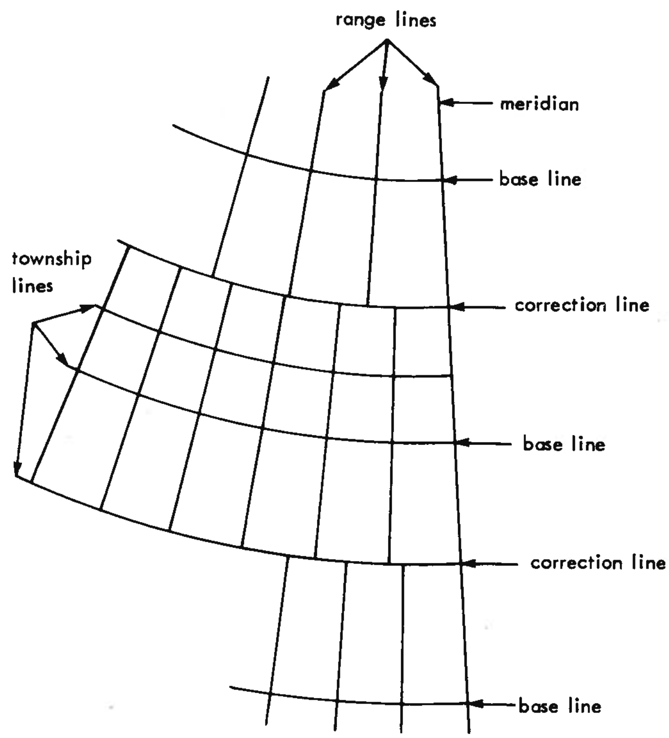


FIGURE 7.5 Dominion Land Survey grid

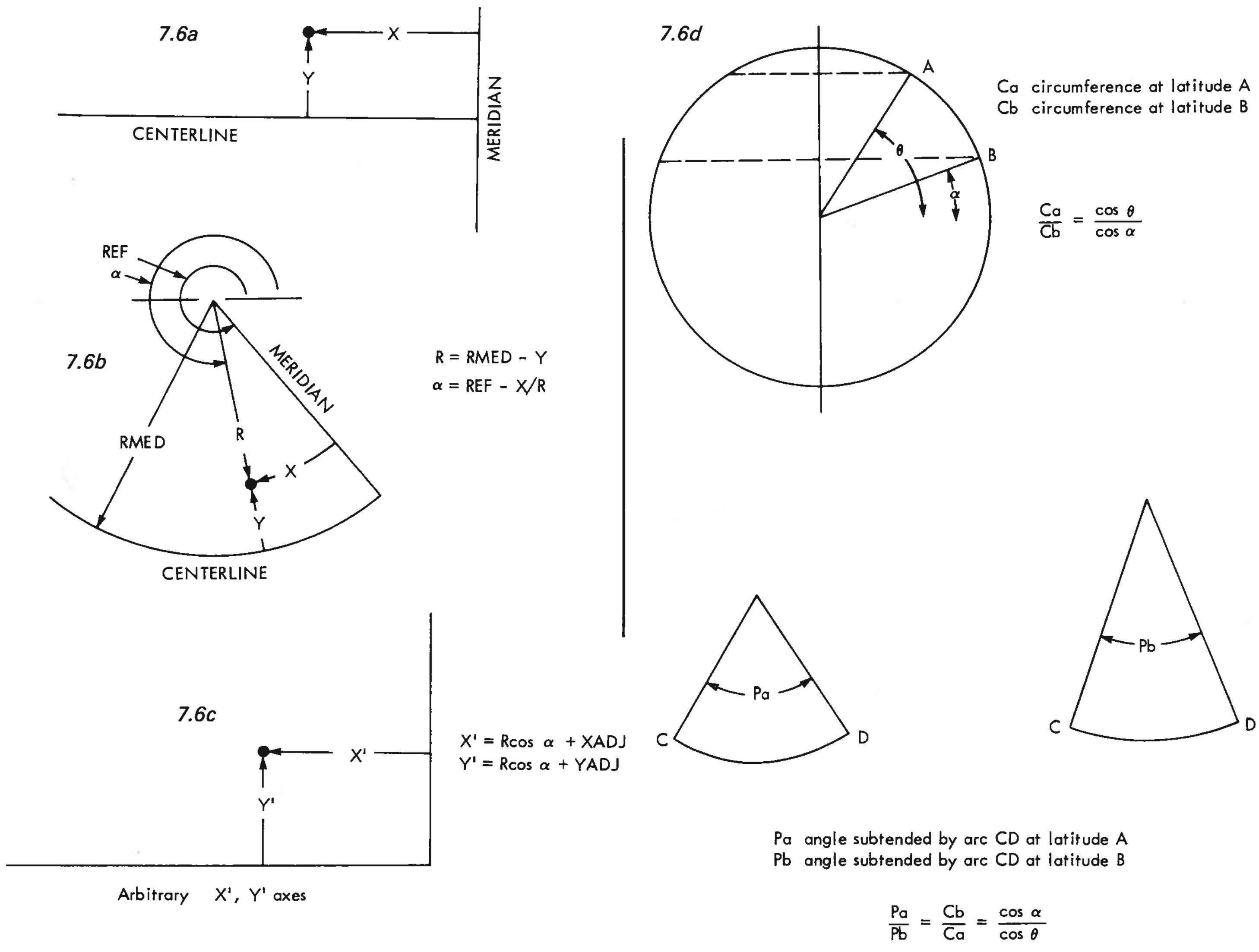
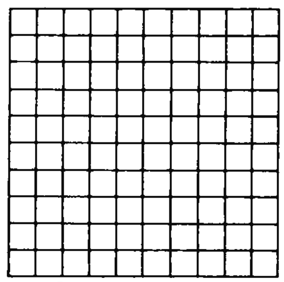
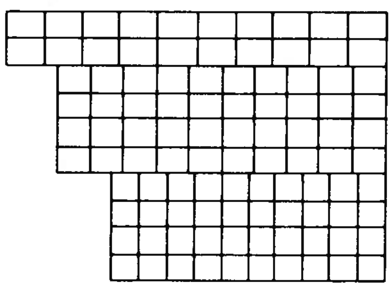


FIGURE 7.6 Illustration of mathematical relationships used in developing the computer programs

7.7a ORIGINAL



7.7b EFFECT OF XWARP



7.7c EFFECT OF ACONE

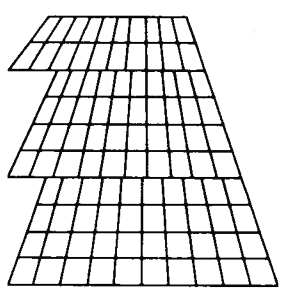


FIGURE 7.7 The original township grid and the geometric effects of subroutines XWARP and ACONE on it

relevant to that strip. This treatment produces an orthogonal grid of township and range lines in which the horizontal scale increases upwards in discrete jumps every 24 miles (Fig. 7.7b). The scale is now true only on the horizontal center line. Then the scale is decreased upward, a continous function of the height of a cone in such a manner as to make no scale change at the horizontal center line. The height of the cone of projection is used for this calculation (Fig. 7.7c).

All coordinates generated up to this point are X and Y orthogonal coordinates (Fig. 7.6a) — the X-coordinate being referenced to the relevant meridian, the Y-coordinate being referenced to the horizontal reference line. The next step is to curve east-west lines by converting to polar coordinates. This is done in two steps. First, X components are considered to be arc lengths and Y components to be lengths in the radial direction. Second, all coordinates are put into the polar form of angles and radii. The horizontal center line becomes an arc at distance RMED from the center of projection (C). The relationship used for radius is $R = RMED - Y$; R being the radial distance (miles) of the point from C. The arcs representing X components are converted to angular measure using R as a radius (Fig. 7.6b). For angular distance, $\emptyset = REF - X\ R$; where $\emptyset$ is the angle and REF is a radial reference line established in such a manner as to center the projection around the $3/2\pi$, 270 degrees radial. The resulting polar coordinates are then translated back to orthogonal coordinates for machine plotting, using the relationships $X' = R_{cos}\emptyset + XADJ$ and $Y' = R_{sin}\emptyset + YADJ$ (Fig. 7.6c). The reference axes are translated using factors XADJ and YADJ which result in a plot that minimizes paper used in the plot.

Since each map sheet has a slightly different geometry from that produced by the initial program, two adjustment parameters were added: one which adjusts the scale in the radial direction and one which adjusts it in the tangential direction. These parameters are factors approximately equal to unity and are linearly and directly proportional to desired scale changes.

This program has been tested on several existing data files and acceptable plots generated. The testing has so far been limited to 1:250,000 scale maps. An accurate method for predetermining the adjustment factors was found.

This program, as implemented on the CalComp 925/1036, has been used extensively for over a year. DLSPLOT appears to have achieved its aims of simplicity and flexibility of operation. It is being used by individuals with no previous computing experience after as little as 2 hours of preparatory instruction. Slightly more complex versions are being used to plot well symbols and chemical diagrams on maps. These latter plots are often done in three colors, using the plotter's three pen capacity.

Listing of DLSPLOT are available upon request.

INSTRUCTIONS FOR USE OF DLSPLOT

The program DLSPLOT was developed for use on the University of Alberta's IBM 360 in Fortran IV. To obtain plots of data using this program and system, *PLOTLIB and *CALCOMPQ, two programs in public files, are also required.

DLSPLOT prompts the user for input, as well as giving him various choices of what is to be plotted. For example, a DLS grid, a symbol or a value may be plotted. Also, any combination of these in various sizes can be chosen.

Two storage files are necessary — one for input data and one for storing plot coordinates. In the following explanation and in the sample runs the input data is in file "ATOBJ" and plotted coordinates in "-PLOT".

In the following description, computer-written lines are in bold face and keyed-in replies are in italics. To initiate the program after signing on the following is keyed in:

*R DLSPLOT+*PLOTLIB 7 = ATOBJ 9=-PLOT*

The machine replies with a number indicating the time and:

DLSPLOT ROUTINE
FIRST TOWNSHIP I3

The machine is asking for the first township to be plotted. I3 indicates that the reply must be given as a three digit integer.

001
This is the reply for township 1

LAST TOWNSHIP I3
010

FIRST RANGE I2
14

LAST RANGE I2
28

Thus far the machine has been told that the area in question covers from township 1 to township 10, and from range 14 to range 28.

SCALE 1: F8.0

The machine is asking for the scale of the plot and requires the answer as a real number with a maximum of seven digits to the left of the decimal and one or none to the right of the decimal (to a maximum of seven digits altogether).

250000.
The decimal point is necessary and must be in the correct place.

VERTICAL ADJUSTMENT 1.0 NONE F8.6

The machine is asking for the vertical adjustment factor and will next ask for the horizontal adjustment factor. A quick and accurate method of determining these factors consists of measuring the distance spanned by four ranges and four townships. This is then compared to the same distance on the uncorrected plot. The factor thus consists of the map distance divided by the corresponding plot distance. In the sample case the answer is 1.0041.

1.0041

HORIZONTAL ADJUSTMENT 1.0 NONE F8.6
1.0123

RUN GRID? YES=1, NO=0

The program is offering a choice of plotting or not plotting a grid.

1

YOUR VARIABLES HAVE BEEN READ IN AS FOLLOWS —
FIRST TOWNSHIP — 01
LAST TOWNSHIP — 10
FIRST RANGE — 14
LAST RANGE — 28
SCALE, 1/250000.

YOUR PLOT WILL NOT BE LONGER THAN 9. INCHES
CONTINUE? YES=22, TRY AGAIN=24, NO=25

The machine has just listed the input data for visual checking, and has included an estimate of the length of the resulting plot. A choice is then offered. If inputted data is incorrect, 24 is typed and the computer will respond by returning to the beginning of the routine. If 22 is typed, the computer will proceed to the next step and if 25 is typed the program is terminated.

22

DO YOU WISH TO PLOT A SYMBOL — YES=1, NO=0
1

WHICH SYMBOL? FORMAT I3, REF.-CALCOMP MANUAL
014

The machine has just asked if a symbol is to be plotted. If yes, the code number of the correct symbol is keyed in. All symbols are referenced in the U of A CALCOMP Manual (1974). In this case a star was wanted and its code number is 014.

SIZE OF SYMBOL IN INCHES? F4.3
.07

The machine has asked for the size required for the symbol to be printed; in this case 07 was the reply.

DO YOU WISH TO PLOT A NUMBER — YES=1, NO=0
1

SIZE OF NUMBER IN INCHES? F4.3
.07

ROUNDING? NUMBER OF DIGITS RIGHT OF DECIMAL? I2
-1

The computer has just asked if numbers are to be plotted and if so, how large they are to be printed and how many decimal places they are to have. An answer of 1 would result in one decimal place. An answer of 0 would produce a number of the form '15.', and the answer -1 produces a number such as "15".

ANGLES (DEGREES) OF NUMBER PLOT I3
020

The machine has asked at what angle the numbers are to be printed relative to the horizontal and an answer of 020 has been given.

INPUT FILE FORMAT? MER, TP, RG, S, LSD, VALUE ENTIRE INPUT MUST BE REAL (F) NUMBERS
(7X, 5F8.0, 8X, F8.1)

The machine has asked for the format by which the variables are to be read from the input file and has stipulated that all values be real numbers. The brackets are necessary and so is the F format. In the above example the computer is to read the data as: count seven spaces then read the first five variables, each of which is eight spaces long and has no non-integer value, then skip eight spaces and read the sixth variable which occupies no more than eight spaces and has no more than one decimal place. Another format might be (7X, 6F5.0) which tells the computer to skip seven spaces then read six variables each of which occupies no more than five spaces and has no numbers to the right of the decimal point. This format is governed by the format of the data as it is put into the storage file, in this case "ATOBJ".

DO YOU WISH TO TRY AGAIN? — YES=1, NO=0
0

The program gives the option of reentering the last information. If this is not required the computer completes the routine and responds with a set of numbers indicating that it has completed the operation. The entire plot is now in the output file, in this case "-PLOT". To get the plot on paper another system routine is required. At the University of Alberta, this is CALCOMPQ. To start the routine the following is typed in:

*R *CALCOMPQ SCARDS = -PLOT*

This tells the computer to run *CALCOMPQ and to get the data it needs from -PLOT. The machine responds with a number indicating the time of the beginning of the run. This is followed by a receipt number for the plot and its estimated dimensions. Finally, when the plot is complete, more numbers will appear indicating that the run is finished.

ACKNOWLEDGMENTS

For providing assistance with the programming, I wish to thank R. Bibby and W. Nielsen. Thanks are also due to L. M. Sebert of the Topographical Survey Directorate and R. E. Moore of the Surveys and Mapping Branch for assistance in explaining the NTS map projections, and to R. Bibby, R. I. Vogwill, R. Green and A. Campbell for editing this paper.

REFERENCES

Sebert, L. M. (1970): Every square inch; Department of Energy, Mines and Resources, Ottawa, 25 pages.

APPENDIX

Sample Runs of DLSPLOT

Sample Runs of DLSPLOT

Five sample runs were made on an existing file, ATOBJ, which contained DLS coordinates of data points in NTS map sheet 73L, Sand River. A portion of this map sheet consisting of the area within townships 58-63, ranges 1-5, was plotted, changing parameters on each run. The sixth run shows reaction of the program to several input errors.

Table 7.1 is a portion of the input data. The numbers plotted on some of the sample runs were the apparent safe yields, Q_{20app}, in ATOBJ.

Table 7.1 Sample portion of input for DLSPLOT

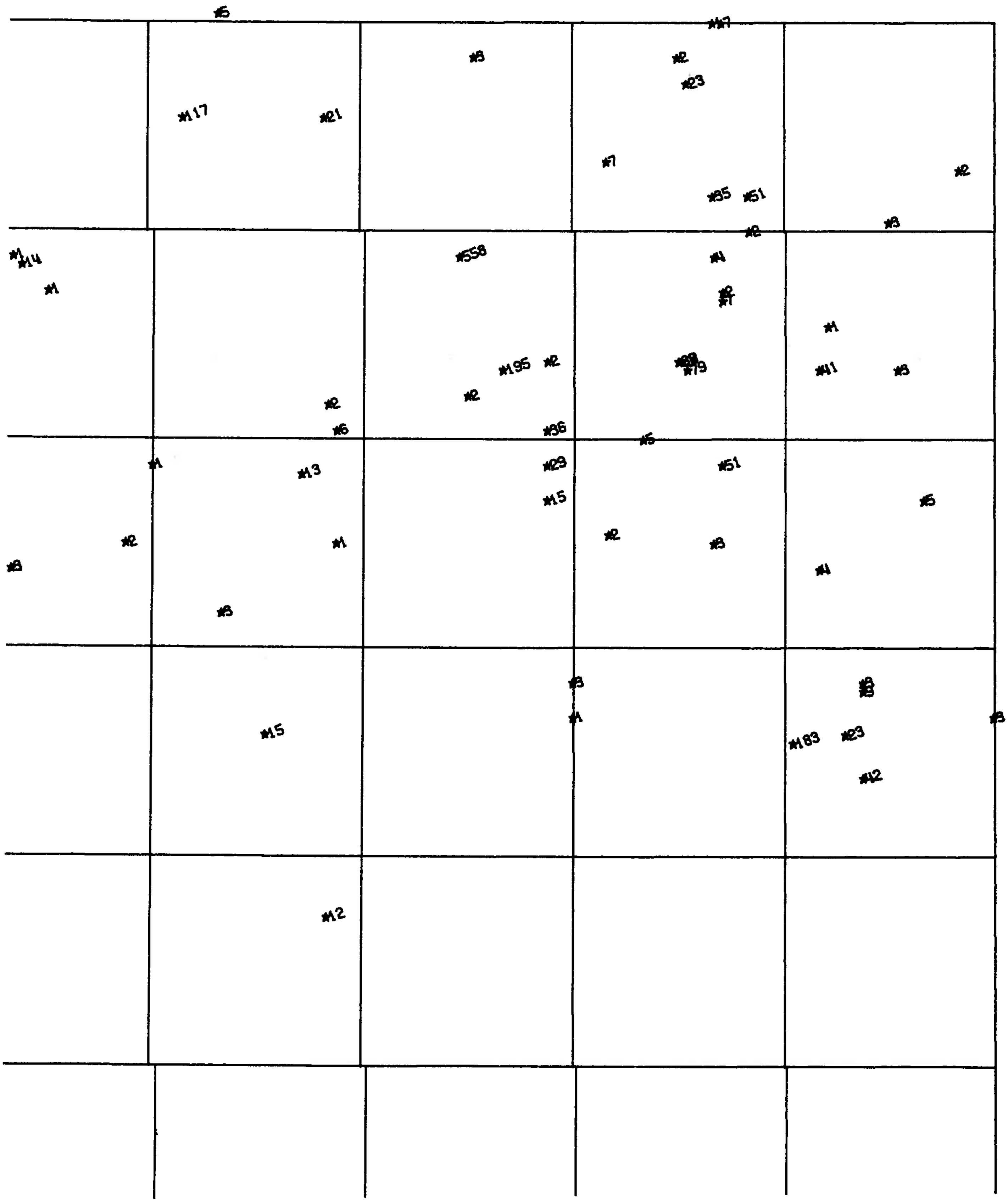
	LEGEND	M	T	R	S	LSD	Tapp	Q20app
>	1	4.0	58.0	5.0	10.0	4.0	697.1	3.3
>	2	4.0	58.0	5.0	10.0	4.0	1038.2	4.9
>	3	4.0	58.0	6.0	7.0	4.0	403.5	11.3
>	4	4.0	58.0	7.0	1.0	13.0	415.7	2.8
>	5	4.0	58.0	7.0	6.0	4.0	1466.5	25.7
>	6	4.0	58.0	7.0	15.0	4.0	36.9	0.9
>	7	4.0	58.0	7.0	25.0	1.0	412.0	1.0
>	8	4.0	58.0	8.0	9.0	1.0	328.0	9.4
>	9	4.0	58.0	8.0	10.0	16.0	76.9	4.2
>	10	4.0	58.0	8.0	14.0	4.0	122620.5	11622.8
>	11	4.0	58.0	8.0	22.0	13.0	912.1	9.5
>	12	4.0	58.0	9.0	1.0	1.0	1344.9	148.5
>	13	4.0	58.0	9.0	2.0	13.0	805.1	35.1
>	14	4.0	58.0	9.0	6.0	16.0	3814.9	115.7
>	15	4.0	58.0	9.0	7.0	16.0	145.4	9.4
>	16	4.0	58.0	9.0	7.0	16.0	704.5	67.8
>	17	4.0	58.0	9.0	7.0	4.0	354.0	7.9
>	18	4.0	58.0	9.0	9.0	16.0	3155.9	239.3
>	19	4.0	58.0	9.0	16.0	1.0	1186.7	52.3
>	20	4.0	58.0	9.0	16.0	16.0	136.2	6.1
>	21	4.0	58.0	10.0	1.0	13.0	806.9	51.2
>	22	4.0	58.0	10.0	5.0	1.0	1469.1	27.9
>	23	4.0	58.0	10.0	7.0	13.0	351.9	10.3
>	24	4.0	58.0	10.0	8.0	1.0	668.5	31.7
>	25	4.0	58.0	10.0	8.0	13.0	458.4	15.6

Sample Run #1

In this run symbols, values, and a grid are called and plotted.

```
a
UNIV OF ALBERTA COMPUTING SERVICES
MTS (0042-FE93/22/0F)
#sig
#PASSWORD?
?[redacted]
#ON AT 12:47.52 ON TUE MAR 04/75 LAST ON AT 12:43.59
#r dlsplot +*plotlib 9=-plot 7=atobj
#12:49.02

DLSPLOT ROUTINE

FIRST TOWNSHIP 13
058

LAST TOWNSHIP 13
063

FIRST RANGE 12
01

LAST RANGE 12
05

SCALE 1:    F8.0
250000.

VERTICAL ADJUSTMENT 1.0=NONE F8.6
1.0041

HORIZONTAL ADJUSTMENT 1.0=NONE F8.6
1.0123

RUN GRID? YES=1,NO=0
1

YOUR VARIABLES HAVE BEEN READ IN AS FOLLOWS-
FIRST TOWNSHIP- 58
LAST TOWNSHIP- 63
FIRST RANGE-  1
LAST RANGE-  5
SCALE, 1/ 250000.
YOUR PLOT WILL NOT BE LONGER THAN 9.INCHES

CONTINUE? YES=22,TRY AGAIN=24,NO=25
22
```

```
DO YOU WISH TO PLOT A SYMBOL-YES=1,NO=0
1

WHICH SYMBOL? FORMAT-13,REF.-CALCOMP MANUAL
014

SIZE OF SYMBOL IN INCHES? F4.3
.07

DO YOU WISH TO PLOT A NUMBER-YES=1,NO=0
1

SIZE OF NUMBER IN INCHES? F4.3
.07

ROUNDING? NUMBER OF DIGITS RIGHT OF DECIMAL? 12
-1

ANGLE (DEGREES) OF NUMBER PLOT 13
020

INPUT FILE FORMAT? MER,TP,RG,S,LSD,VALUE
ENTIRE INPUT MUST BE REAL(F)NUMBERS
(7x,5f8.1,8x,f8.1)

DO YOU WISH TO TRY AGAIN?-YES=1,NO=0
0
#12:53.35 4.751 RC=0
#



r *calcompq scards=-plot
#12:54.16
*** CALCOMP RECEIPT #  1046****  PLOT LENGTH = 12 INCHES;
#12:54.31 .924 RC=0
#
```

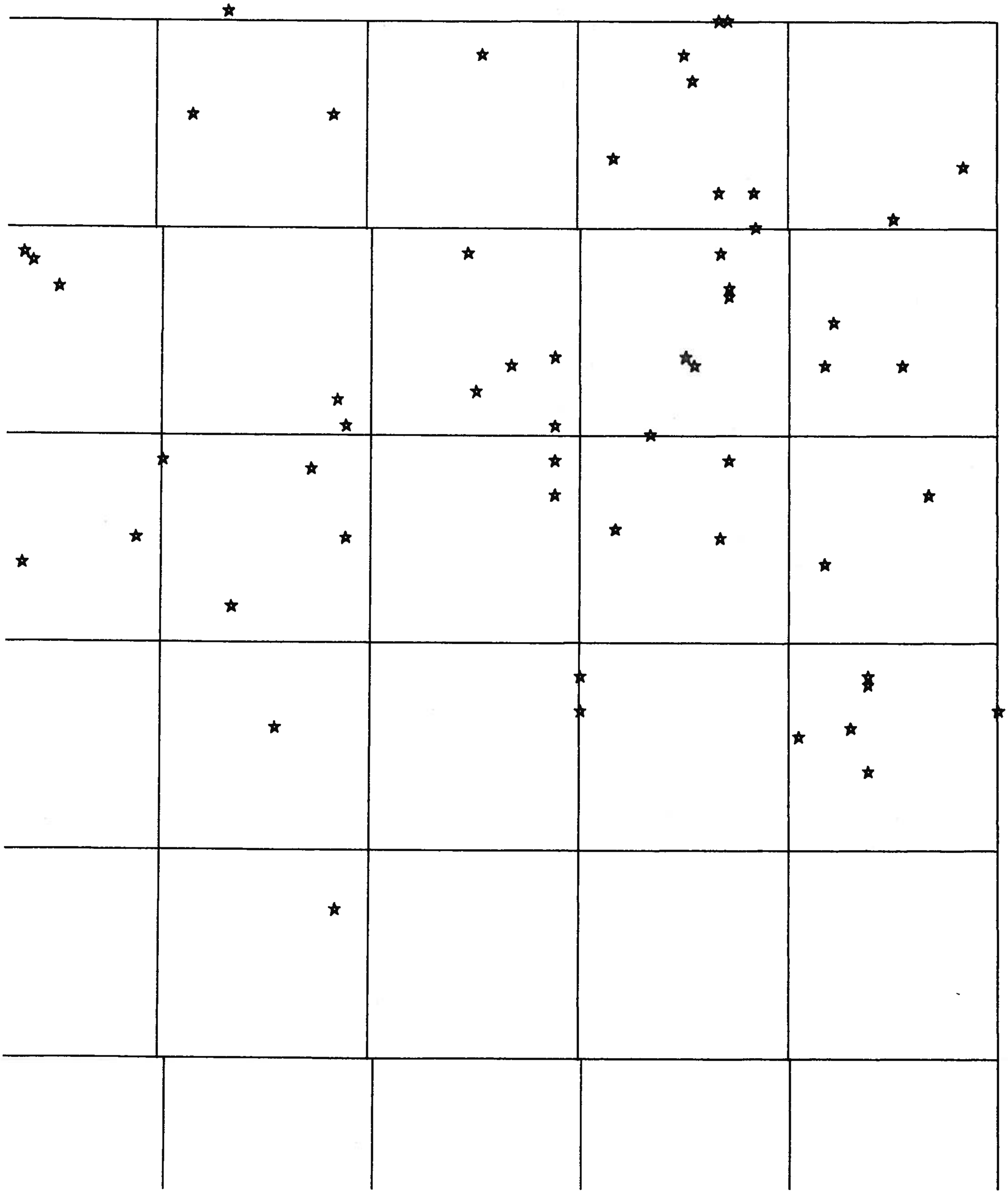

*117
*21
*23
*35
*51
*558
*195
*41
*36
*13
*29
*51
*15
*15
*183
*23
*12

Sample Run #2

In this run symbols and a grid are called and plotted. Note that the symbol has been increased in size relative to run #1.

```
r dlsplot+*plotlib 9=-plot2 7=atobj
#12:56.05

DLSPLOT ROUTINE

FIRST TOWNSHIP 13
058

LAST TOWNSHIP 13
063

FIRST RANGE 12
01

LAST RANGE 12
05

SCALE 1:  F8.0
250000.

VERTICAL ADJUSTMENT 1.0=NONE F8.6
1.0041

HORIZONTAL ADJUSTMENT 1.0=NONE F8.6
1.0123

RUN GRID? YES=1,NO=0
1

YOUR VARIABLES HAVE BEEN READ IN AS FOLLOWS-
FIRST TOWNSHIP- 58
LAST TOWNSHIP- 63
FIRST RANGE-  1
LAST RANGE-  5
SCALE, 1/ 250000.
YOUR PLOT WILL NOT BE LONGER THAN 9.INCHES

CONTINUE? YES=22,TRY AGAIN=24,NO=25
22

DO YOU WISH TO PLOT A SYMBOL-YES=1,NO=0
1

WHICH SYMBOL? FORMAT-13,REF.-CALCOMP MANUAL
014
```

```
SIZE OF SYMBOL IN INCHES? F4.3
.1

DO YOU WISH TO PLOT A NUMBER-YES=1,NO=0
0

INPUT FILE FORMAT? MER,TP,RG,S,LSD
ENTIRE INPUT MUST BE REAL(F)NUMBERS
(7x,5f8.1)

DO YOU WISH TO TRY AGAIN?-YES=1,NO=0
0
#13:00.12 3.476 RC=0
#



r *calcompq scards=-plot2
#13:00.46
*** CALCOMP RECEIPT #  1047****  PLOT LENGTH =  12 INCHES;
#13:01.14 .715 RC=0
#
```

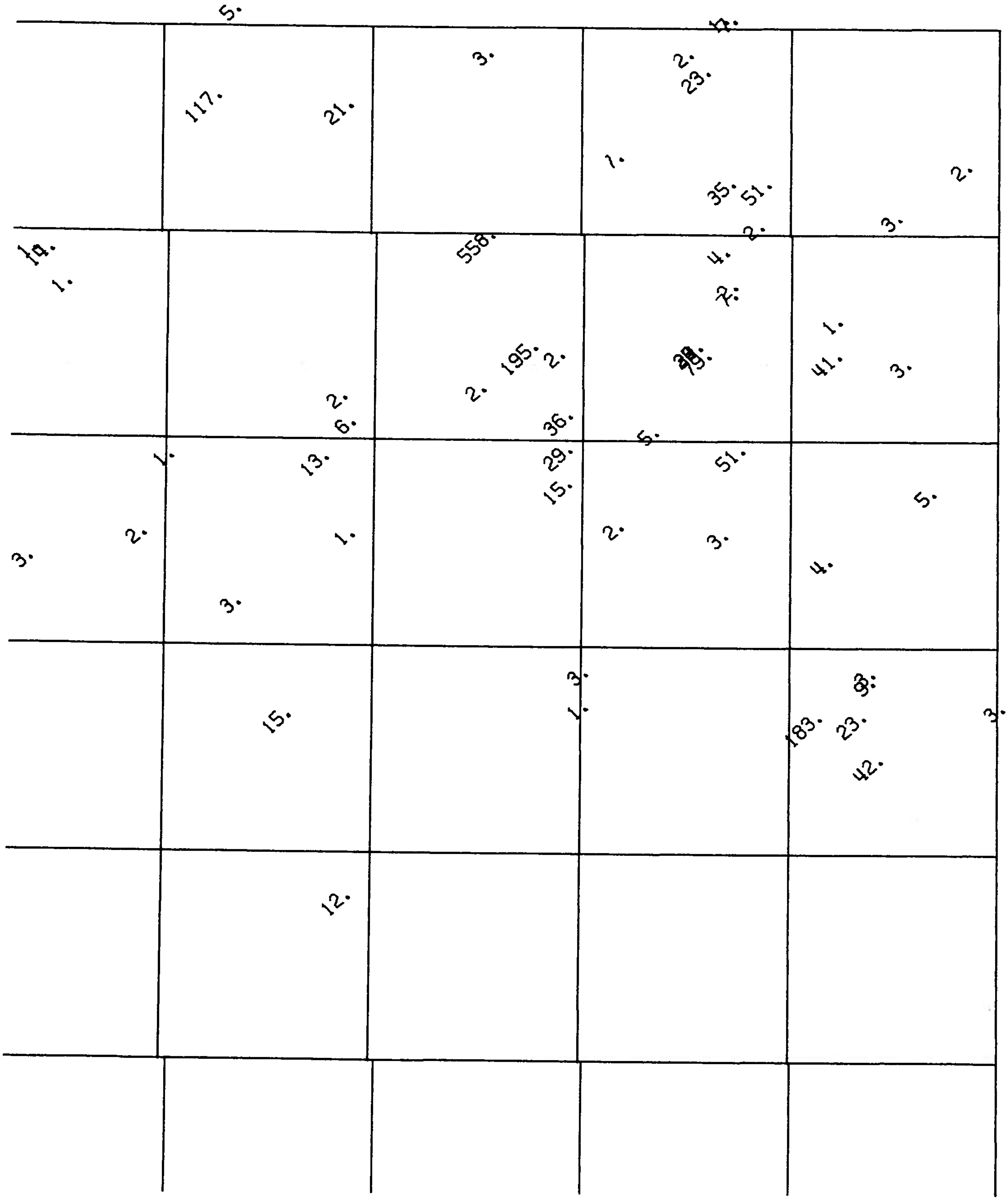


Sample Run #3

In this run numbers, values, and a grid were called and plotted. Note the numbers have been increased in size and plotted at a greater angle relative to run #1. Also note that the rounding factor has been changed from -1 as it is in run #1 to 00 resulting in the decimal point being plotted.

```
r dlsplot+*plotlib 7=atobj 9=-plot3
#13:02.58

DLSPLOT ROUTINE

FIRST TOWNSHIP 13
058

LAST TOWNSHIP 13
063

FIRST RANGE 12
01

LAST RANGE 12
05

SCALE 1:    F8.0
250000.

VERTICAL ADJUSTMENT 1.0=NONE F8.6
1.0041

HORIZONTAL ADJUSTMENT 1.0=NONE F8.6
1.0123

RUN GRID? YES=1,NO=0
1

YOUR VARIABLES HAVE BEEN READ IN AS FOLLOWS-
FIRST TOWNSHIP- 58
LAST TOWNSHIP- 63
FIRST RANGE-  1
LAST RANGE-  5
SCALE, 1/ 250000.
YOUR PLOT WILL NOT BE LONGER THAN 9.INCHES

CONTINUE? YES=22,TRY AGAIN=24,NO=25
22

DO YOU WISH TO PLOT A SYMBOL-YES=1,NO=0
0
```

```
DO YOU WISH TO PLOT A NUMBER-YES=1,NO=0
1

SIZE OF NUMBER IN INCHES? F4.3
.1

ROUNDING? NUMBER OF DIGITS RIGHT OF DECIMAL? 12
00

ANGLE (DEGREES) OF NUMBER PLOT 13
045

INPUT FILE FORMAT? MER,TP,RG,S,LSD,VALUE
ENTIRE INPUT MUST BE REAL(F)NUMBERS
(7x,5f8.1,8x,f8.1)

DO YOU WISH TO TRY AGAIN?-YES=1,NO=0
0
#13;08.40 4.623   =0
#



r *calcompq scards=-plot3
#13:09.25
*** CALCOMP RECEIPT #  1048****  PLOT LENGTH =  12 INCHES;
#13:09.33 .899 RC=0
#
```



Sample Run #4

In this run symbols and numbers were plotted. Note the increased angle of the number plot and the change of symbol relative to run #1.

```
#r dlsplot+*plotlib 7=atobj 9=-plot4
#13:11.36

DLSPLOT

FIRST TOWNSHIP 13
058

LAST TOWNSHIP 13
063

FIRST RANGE 12
01

LAST RANGE 12
05

SCALE 1:    F8.0
250000.

VERTICAL ADJUSTMENT 1.0=NONE F8.6
1.0041

HORIZONTAL ADJUSTMENT 1.0=NONE F8.6
1.0123

RUN GRID? YES=1,NO=0
0

YOUR VARIALBES HAVE BEEN READ IN AS FOLLOWS-
FIRST TOWNSHIP- 58
LAST TOWNSHIP- 63
FIRST RANGE-  1
LAST RANGE-  5
SCALE, 1/ 250000.
YOUR PLOT WILL NOT BE LONGER THAN 9.INCHES

CONTINUE? YES=22,TRY AGAIN=24,NO=25
22

DO YOU WISH TO PLOT A SYMBOL-YES=1,NO=0
1

WHICH SYMBOL? FORMAT-13,REF.-CALCOMP MANUAL
075
```

```
SIZE OF SYMBOL IN INCHES? F4.3
.2

DO YOU WISH TO PLOT A NUMBER-YES=1,NO=0
1

SIZE OF NUMBER IN INCHES? F4.3
.05

ROUNDING? NUMBER OF DIGITS RIGHT OF DECIMAL? 12
-1

ANGLE (DEGREES) OF NUMBER PLOT 13
070

INPUT FILE FORMAT? MER,TP,RG,S,LSD,VALUE
ENTIRE INPUT MUST BE REAL(F)NUMBERS
(7x,5f8.1,8x,f8.1)

DO YOU WISH TO TRY AGAIN?-YES=1,NO=0
0
#13:17.52 4.031 RC=0
#


r *calcompq scards=-plot4
#13:18.32
*** CALCOMP RECEIPT #  1049****  PLOT LENGTH =  12 INCHES;
#13:18.39 .758 RC=0
#
```

Sample Run #5

In this run only the grid was called for.

```
r dlsplot+*plotlib 9=-plot5 7=atobj
#13:20.53

DLSPLOT ROUTINE

FIRST TOWNSHIP 13
058

LAST TOWNSHIP 13
063

FIRT

FIRST RANGE 12
01

LAST RANGE 12
05

SCALE 1:   F8.0
250000.

VERTICAL ADJUSTMENT  1.0=NONE F8.6
1.0041

HORIZONTAL ADJUSTMENT  1.0=NONE F8.6
1.0123

RUN GRID? YES=1,NO=0
1

YOUR VARIABLES HAVE BEEN READ IN AS FOLLOWS-
FIRST TOWNSHIP- 58
LAST TOWNSHIP- 63
FIRST RANGE-  1
LAST RANGE-  5
SCALE, 1/ 250000.
YOUR PLOT WILL NOT BE LONGER THAN 9.INCHES

CONTINUE? YES=22,TRY AGAIN=24,NO=25
22

DO YOU WISH TO PLOT A SYMBOL-YES=1,NO=0
0

DO YOU WISH TO PLOT A NUMBER-YES=1,NO=0
0
```

```
DO YOU WISH TO TRY AGAIN?-YES=1,NO=0
0
#13:23.49 1.404 RC=0
#


 r *calcompq scards=-plot5
#13:25.16
*** CALCOMP RECEIPT #  1050****  PLOT LENGTH =  12 INCHES
```


Sample Run #6

This run was not plotted. It is an illustration of obvious errors in input, the programmed reaction to such errors, the method of correcting input, and the terminating of program execution.

```
r dlsplot+*plotlib 9=-plot6 7=atobj
#13:34.47

DLSPLOT ROUTINE

FIRST TOWNSHIP 13
015

LAST TOWNSHIP 13
001

FIRST RANGE 12
01

LAST RANGE 12
05

SCALE 1:    F8.0
250000.

VERTICAL ADJUSTMENT 1.0=NONE F8.6
1.

HORIZONTAL ADJUSTMENT 1.0=NONE F8.6
1.

RUN GRID? YES=1,NO=0
1

YOUR VARIABLES HAVE BEEN READ IN AS FOLLOWS-
FIRST TOWNSHIP- 15
LAST TOWNSHIP- 1
FIRST RANGE-  1
LAST RANGE-  5
SCALE, 1/ 250000.
YOUR PLOT WILL NOT BE LONGER THAN 9.INCHES

CONTINUE? YES=22,TRY AGAIN=24,NO=25
22
SOMETHING WRONG WITH LOCATIONS

YOUR VARIABLES HAVE BEEN READ IN AS FOLLOWS-
FIRST TOWNSHIP- 15
LAST TOWNSHIP-  1
```

```
FIRST RANGE-  1
LAST RANGE-  5
SCALE, 1/ 250000.
YOUR PLOT WILL NOT BE LONGER THAN 9.INCHES

CONTINUE? YES=22,TRY AGAIN=24,NO=25
24

DLSPLOT ROUTINE

FIRST TOWNSHIP 13
001

LAST TOWNSHIP 13
015

FIRST RANGE 12
01

LAST RANGE 12
01

SCALE 1:   F8.0
250000.

VERTICAL ADJUSTMENT 1.0=NONE F8.6
1.

HORIZONTAL ADJUSTMENT 1.0=NONE F8.6
1.

RUN GRID? YES=1,NO=0
1


YOUR VARIABLES HAVE BEEN READ IN AS FOLLOWS -
FIRST TOWNSHIP-  1
LAST TOWNSHIP- 15
FIRST RANGE-  1
LAST RANGE-  1
SCALE, 1/ 250000.
YOUR PLOT WILL NOT BE LONGER THAN 2.INCHES

CONTINUE? YES=22,TRY AGAIN=24,NO=25
22
SOMETHING WRONG WITH LOCATIONS

YOUR VARIABLES HAVE BEEN READ IN AS FOLLOWS-
FIRST TOWNSHIP-  1
LAST TOWNSHIP- 15
```

```
FIRST RANGE-  1
LAST RANGE-  1
SCALE, 1/ 250000.
YOUR PLOT WILL NOT BE LONGER THAN 2.INCHES


CONTINUE? YES=22,TRY AGAIN=24,NO=25
25
#13:41.02 .866 RC=0
#
```

ERRATA SHEET -- BULLETIN 35

On page 45, in the legend of Figure 5.2, the symbol for observation wells should be an open circle.

On page 45, left column, paragraph 1, line 3 should read:
"enabled repair and reinforcing of the roof (Plate 5.3)."

On page 56, the second equation in the first column should be:

$$\frac{\partial q_x}{\partial_x} + \frac{\partial q_y}{\partial_y} + \frac{\partial q_z}{\partial_z} = 0$$

On page 57, left column, second paragraph, line 4 should read:
"conditions can be applied. Such boundaries are basically of"

On page 57, left column, fourth paragraph, line 5 should read:
"expression $h = \frac{p-p_o}{\rho g} + z$ reduces to h=z. Extensive"

On page 60, left column, second paragraph, lines 6 and 7 should read:
"presently available with resistivities of 1500-2200 Ω/sq,
4000-10,000 Ω/sq, and 8000-20,000 Ω/sq, it is conceivably"

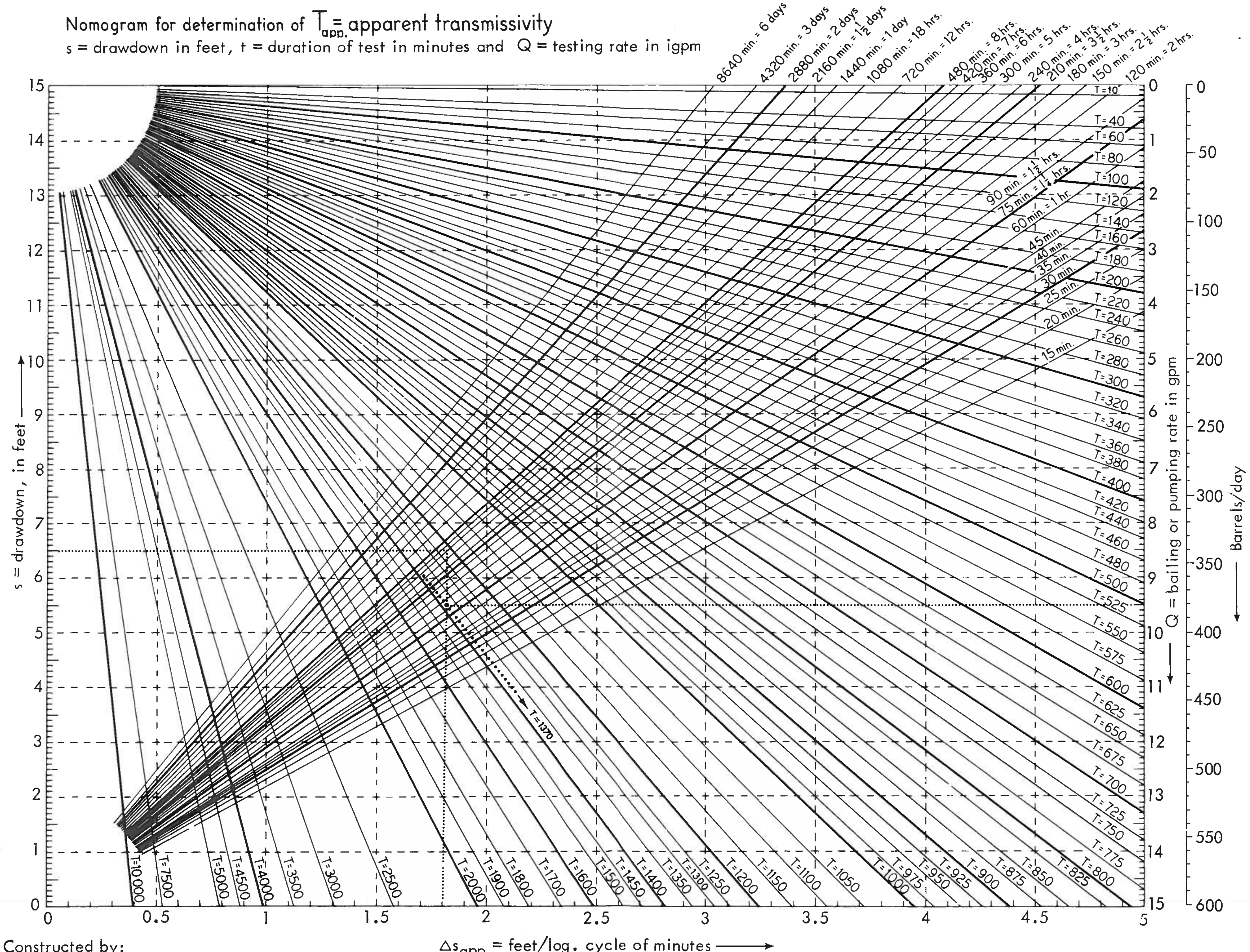
On page 61, left column, fourth paragraph, line 7 should read:
"$(\sigma_x/\sigma_z)^{1/2}$, where σ_x and σ_z are conductivities of the"

On page 65, right column, first paragraph, lines 8, 9 and 10 should read:
"necessary so that it is flat, this forms a UTM zone (Fig. 7.1b).
The province of Alberta is contained within two such zones (Fig. 7.1a).
Each zone ...."

On page 67, in Figure 7.4a, the apex of the cone of projection should be labeled "C".

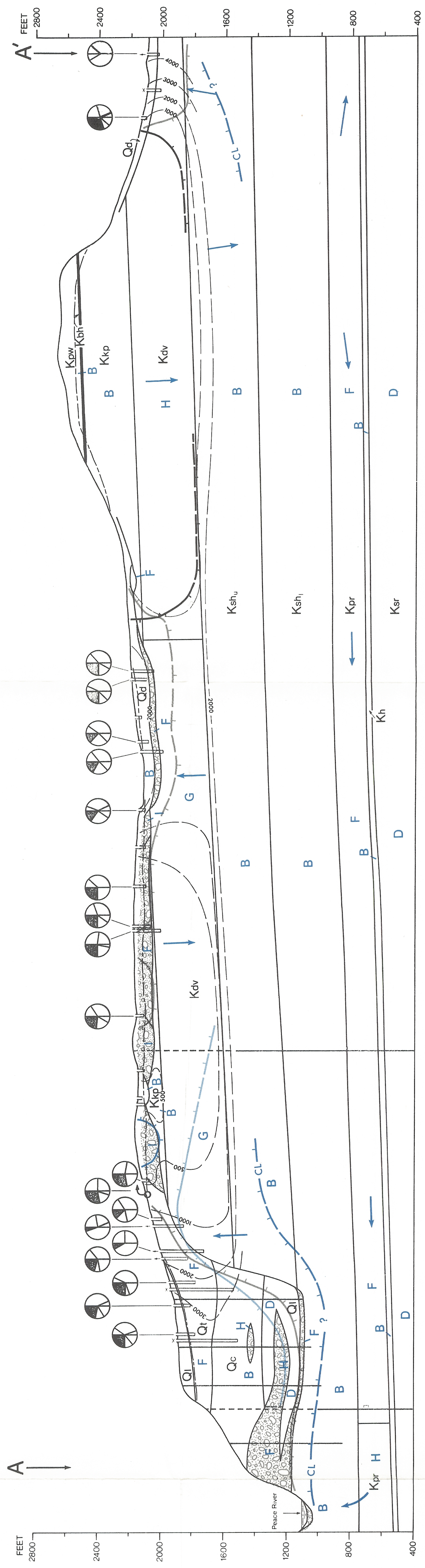
Nomogram for determination of $T_{app.}$ = apparent transmissivity

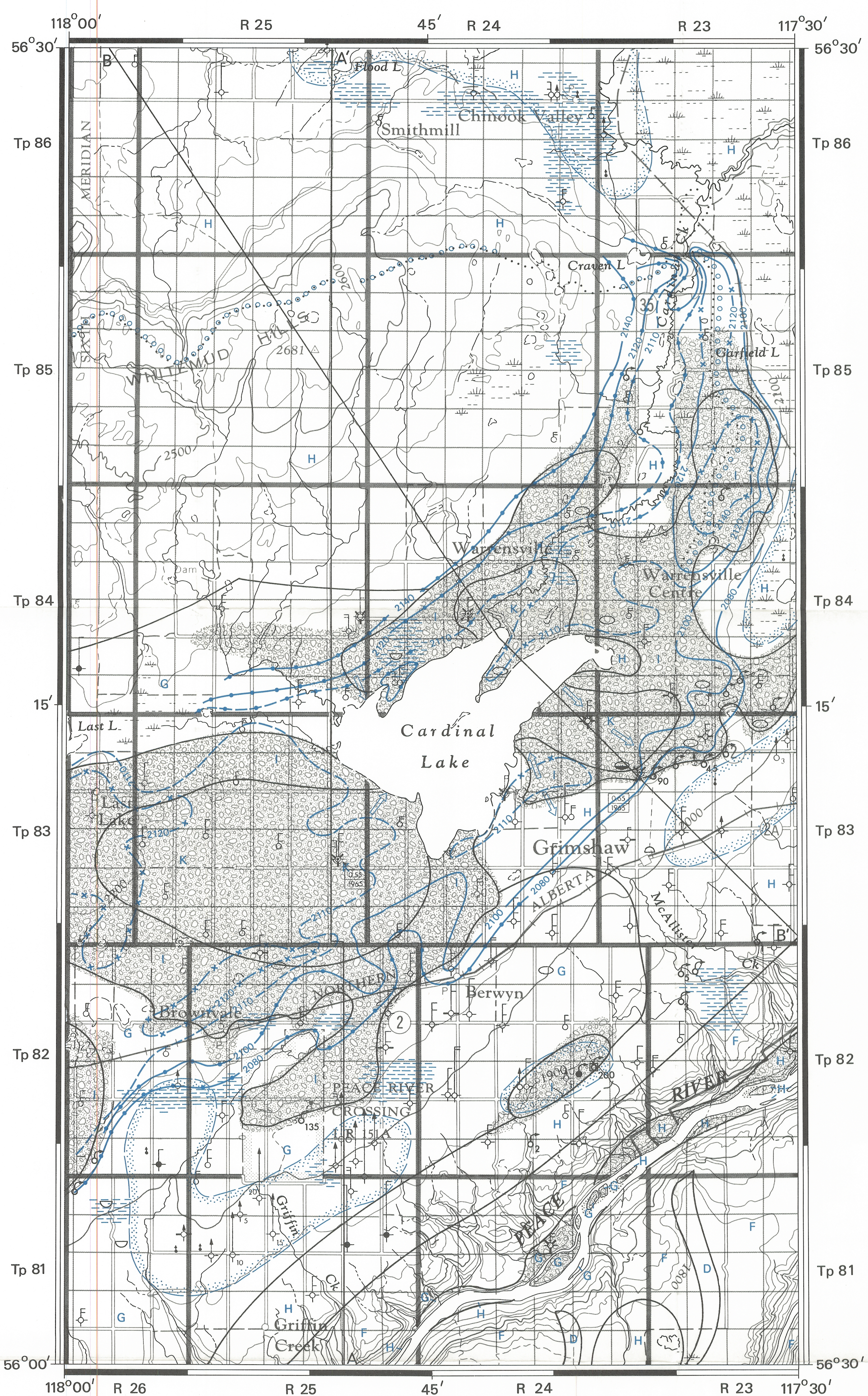
s = drawdown in feet, t = duration of test in minutes and Q = testing rate in igpm

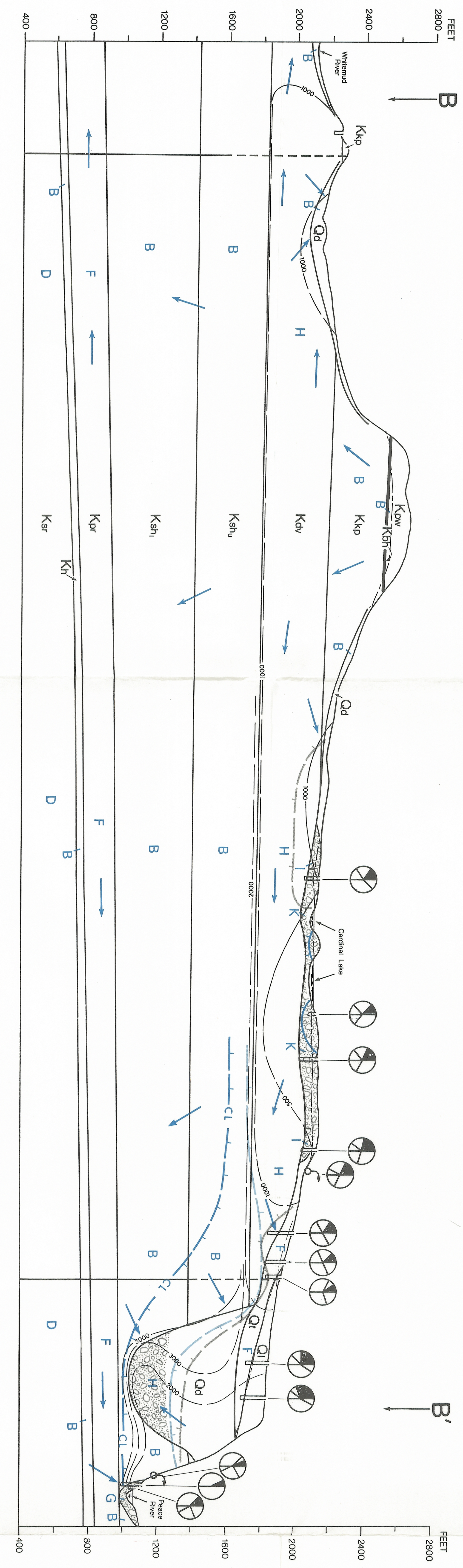


Constructed by:
G. Ozoray, Feb. 1969

Example: s = 6.5 feet
t = 6 hours
Q = 9.5 igpm
T_{app} = 1374; reading ≈ 1370







MAIN MAP LEGEND

Topography

Surface contours (interval 100 feet)

Lithology

Sand and gravel

Hydrography

- Surface water divide
- Spring and flow rate, in imperial gallons per minute
- Spring, inactive
- Natural pond or water hole with no outlet
- Stream
- Stream, intermittent or dry
- Lake
- Lake, intermittent
- Marsh or swamp

Groundwater hydrology

Upward flow

2100 — Water table contour (elevation in feet above mean sea level)

Downward flow

- Direction and calculated velocity of groundwater flow (in feet per day)
- Groundwater divide
- Boundary of area of artesian flow (stipple lies within the boundary)
- Area of salt precipitates
- Nonpumping water level

Boreholes, Wells and other works

- Borehole, seismic shot hole, test hole, etc.
- Location of former flowing seismic shot hole
- Water well, dug or bored
- Water well, dug or bored, flowing, and flow rate in imperial gallons per minute
- Water well, drilled
- FEET 0–500; Depth to water; Depth of well — Water well, drilled (bar shows well depth and depth to water; scale 1 mm = 20 feet)
- FEET 0–300; Depth of well — Water well, drilled, flowing, and flow rate in imperial gallons per minute (length of arrow indicates well depth; scale 1 mm = 20 feet)
- Water well, drilled, nonproductive
- Test well
- Drilled well, site of pump test (24 hours or longer), 20-year safe yield calculated
- Drilled well, site of bail test or short pump test, 20-year safe yield calculated
- Drilled well, safe yield estimated from apparent transmissivity
- Observation well, provided with automatic recorder
- Observation well, recording lake level, provided with automatic recorder
- 0.65 / 1965 — Mean annual water level fluctuation, in feet; Commencement of observations
- Differing water levels from different depths, in same well or closely adjacent wells
- Cistern, storage tank
- Developed spring
- Infiltration gallery
- Water pipeline
- Gravel pit, dry
- Gravel pit, containing water
- A — A' Line of hydrogeological profile

Groundwater Probability*

Average expected yield of wells (in imperial gallons per minute)

established from pump or bail tests, etc.

estimated, from flow regime, lithology, etc.

Established	Estimated	Yield
K		500
I		100
G	H	25
	F	5
	D	1
	B	

*The expected yields of wells are predictions, based on the best data available at the time of map compilation; due to data shortcomings, local variations in geology, well completion techniques and similar noncontrollable factors, less water may be obtainable from some individual wells than the yield range predicted.

SCALE 1:125,000

Miles 5 0 5 10 Miles

Kilometers 5 0 5 10 15 Kilometers

WEST OF FIFTH MERIDIAN

METEOROLOGY

LEGEND

Mean annual precipitation:

- less than 15 inches
- 15 to 20 inches
- Isohyet, mean annual precipitation in inches
- Meteorological station
- Rain gauge only

Precipitation data

12.8+? / 19.2 (E) / 1954 / May–Oct.

- Mean annual rainfall + estimated (1/10) or measured rainfall equivalent of snowfall (? indicates snowfall not measured)
- Mean annual precipitation, in inches (E indicates estimated)
- Commencement of observations
- Months of record if less than full year
- Mean monthly potential evapotranspiration (estimated)
- Mean monthly precipitation
- Period when surface is usually snow-covered
- Period with mean daily temperature below freezing (0° C.)
- Figure indicates percentage of mean annual precipitation falling as rain

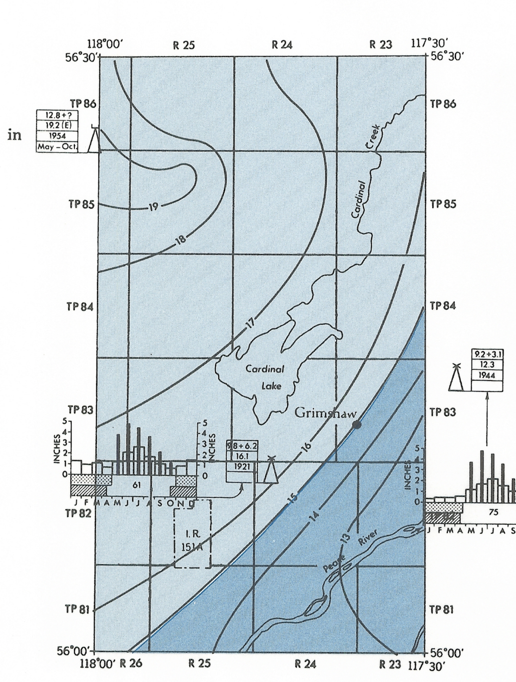
INCHES 0–5; J F M A M J J A S O N D; Months of a year; 75

Source of data: Climatic Maps for Alberta (Longley, 1968) and Monthly Record of Meteorological Observations (Meteorological Branch, Canada Department of Transport)

SCALE 1:500,000

Miles 5 0 5 10 Miles

Kilometers 5 0 5 10 15 Kilometers



HYDROCHEMISTRY

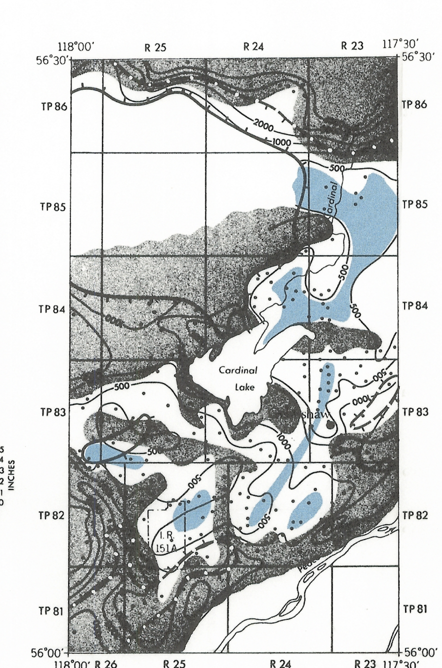
LEGEND

- 1000 — Total dissolved solids, in parts per million
- Sulfate constituting over 60 per cent of total anions, on equivalents per million basis
- Bicarbonate + carbonate constituting over 60 per cent of total anions, on equivalents per million basis
- Isogram along which calcium constitutes 60 per cent of total cations; teeth indicate direction of lesser calcium content
- Isogram along which sodium + potassium constitutes 60 per cent of total cations; teeth indicate direction of lesser sodium + potassium content
- Data point

SCALE 1:500,000

Miles 5 0 5 10 Miles

Kilometers 5 0 5 10 15 Kilometers



IRON CONTENT

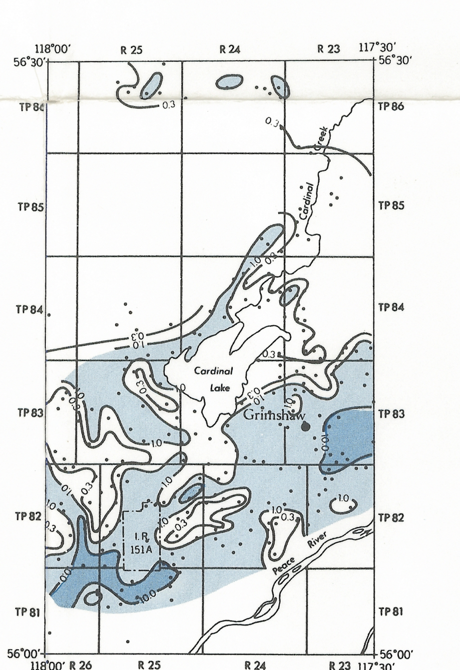
LEGEND

- 0.3 — Iron content in parts per million
- Iron content ranging between 1.0 and 10 parts per million
- Iron content over 10 parts per million
- Data point

SCALE 1:500,000

Miles 5 0 5 10 Miles

Kilometers 5 0 5 10 15 Kilometers



CALCIUM-MAGNESIUM RATIO

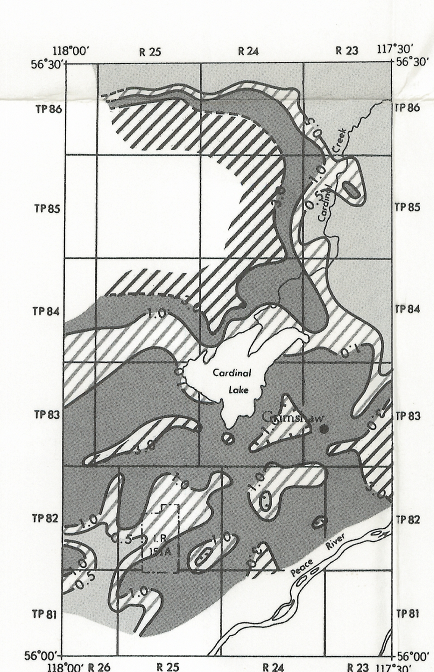
LEGEND

- < 0.5
- 0.5 to 1.0
- 1.0 to 3.0
- > 3.0
- good control
- poor control

SCALE 1:500,000

Miles 5 0 5 10 Miles

Kilometers 5 0 5 10 15 Kilometers



HYDROGEOLOGICAL MAP
GRIMSHAW - CHINOOK VALLEY
NTS 84C/4 AND 84C/5
ALBERTA

HYDROGEOLOGICAL PROFILE LEGEND

(horizontal scale same as main map scale; vertical scale: 1 cm = 200 ft.; vertical exaggeration about 20x)

Geology

QUATERNARY

- Qd — Drift: *unconsolidated surficial deposits*
- Qt — Till, clayey: *local pockets of sand and gravel*
- Qc — Clay and silty clay: *lacustrine and slack water deposits*
- Ql — Clay, silt: *lacustrine deposits*

UPPER CRETACEOUS

- Kpw — Puskwaskau Formation: *dark grey fissile shale: 0 - 130 feet*
- Kbh — Bad Heart Formation: *black, orange-weathering, oolitic, iron-rich sandstone*
- Kkp — Kaskapau Formation: *dark grey fissile shale, sandy and silty shale, sandstone; 0 - 370 feet*
- Kdv — Dunvegan Formation: *grey silty carbonaceous shale, beds and lenses of grey, soft, clay-cemented sandstone; 0 - 405 feet*
- Ksh_u — Shaftesbury Formation, upper member: *grey silty shale, siltstone lenses; 0 - 460 feet*

LOWER CRETACEOUS

- Ksh_l — Shaftesbury Formation, lower member: *dark grey fissile shale; 270 - 460 feet*
- Kpr — Peace River Formation, Paddy and Cadotte Members: *poorly sorted, fine- to medium-grained sandstone, locally shaly; 100 - 165 feet*
- Kh — Peace River Formation, Harmon Member: *dark grey shale, minor siltstone, sandstone: 40 - 70 feet*
- Ksr — Spirit River Formation: *grey shale, fine-grained sandstone, local coal seams; fine- to medium-grained sandstone in upper part*

Boundary of area of unsaturated zone

Boreholes, wells and other works

- Water well or test well
- Water well, nonproductive
- Water well, flowing, and flow rate in imperial gallons per minute
- Geological test hole
- Exploratory oil or gas well; broken line indicates surface casing interval
- Interval of drill-stem test

Groundwater hydrology and chemistry

- Component of groundwater flow direction

Calcium; Magnesium; Sodium + potassium; 0; 50%; 100%; Carbonate + bicarbonate; Sulfate; Chloride; CATIONS | ANIONS

- 500 — Total dissolved solids, in parts per million
- Isogram along which calcium constitutes 60 per cent of total cations*
- Isogram along which sodium + potassium constitutes 60 per cent of total cations*
- Isogram along which carbonate + bicarbonate constitutes 60 per cent of total anions*
- Isogram along which sulfate constitutes 60 per cent of total anions*
- CL — Isogram along which chloride constitutes 60 per cent of total anions*

*1) determined on equivalents per million basis.
2) teeth indicate direction of lesser cation content

Hydrogeology by O. Tokarsky, 1968, based on data collected in 1965.
Cartographic editing by R. Green; drawn by H. Weiss.

Originally published in 1970 in full color; selected portions of map reprinted in 1977 in two colors, to accompany Bulletin 35.