REGIONAL HYDROGEOLOGICAL STUDY McMURRAY OIL SANDS AREA, ALBERTA

Prepared for the
Oil Sands Environmental Study Group
H. A. Gorrell, P.Geol., Study Coordinator

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The Oil Sands Environmental Study Group

October, 1974

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FOREWORD

The Oil Sands Environmental Study Group (OSESG) is a non-profit organization of 23 leaseholders, development and operating companies involved in the Athabasca, Cold Lake and Peace River Tar Sands deposits. The Group was formed to co-ordinate and sponsor research programs into the environmental implications of tar sand resource development.

In October of 1974, the report "Regional Hydrogeology Study, McMurray Oil Sands Area, Alberta, Phase I" was submitted to the OSESG by Mr. H.A. Gorrell, P. Geol., project co-ordinator for J.C. Sproule and Associates Ltd. This report contained an overview of the hydrogeology of the Athabasca Tar Sands and a comprehensive list of recommendations for further studies. The recommendations have assisted the Alberta Oil Sands Environmental Research Program, the OSESG and its individual member companies is designing hydrogeological research programs.

Syncrude Canada Ltd. has been publishing the results of its environmental research since 1973. The following monograph consists of the hydrogeological data from the original report submitted to the OSESG and is intended as a background document for more site-specific and intensive studies to be published by Syncrude in the future. The recommendations found in the original report have been removed, since in themselves they did not add to the body of hydrogeologic information.

Syncrude Canada Ltd. gratefully acknowledges the co-operation of the Oil Sands Environmental Study Group, J.C. Sproule and Associates, and the contributing authors and advisors, received during the preparation of this publication.

Membership of the Oil Sands Environmental Study Group involved in sponsoring the attached study:

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SUMMARY

In May of 1974, the Oil Sands Environment Study Group (O.S.E.S.G.) authorized a First Phase Regional Hydrogeological Study of the McMurray Oil Sands area in Alberta. The objects of the assigned study were to:

- Determine the present availability of pertinent hydrogeological data.
- Interpret this data as far as possible and outline the effects of the groundwater systems on oil recovery operations and vice versa.
- Determine what additional data is required, recommend methods of obtaining this data, and give initial cost estimates.
- Prepare a report summarizing the results of the work.

The study was undertaken by a group of Alberta consulting hydrogeologists with the assistance of an Advisory and Review Committee comprising recognized Canadian experts in hydrogeology.

The work was initiated by visiting the offices of the member companies of the O.S.E.S.G. and collecting the pertinent data made available by these companies.

Although well in excess of 3,000 holes have been drilled on leases held by the member companies and although these provide considerable basic geological data on the section down to the top of the Devonian, disappointingly little adequate hydrogeological information is available for the area and there is very little detailed geological information available on the Devonian system. Less than one percent of the holes drilled

were carried far enough into the Devonian to provide adequate information on the geology or hydrogeology of this very important unit. There are very few chemical data pertaining to the waters of the various groundwater flow systems and almost no pressure data. Data available are summarized in Table 1, page 35 in the body of the report.

The stratigraphic sequence in the area begins with Precambrian, predominantly crystalline, rocks. These are overlain by a sequence of Devonian rocks, predominantly of the carbonate and evaporitic types, ranging in thickness from over 2,500 feet in the western part of the area to less than 500 feet in the eastern part. The Devonian is unconformably overlain by a Cretaceous section, which includes the McMurray Oil Sands and which ranges in thickness from well over 600 feet in the west to under 100 feet in the east. The Cretaceous is overlain by a thin veneer of glacial and younger beds.

In spite of the paucity of hydrogeological information, it has been possible to make certain interpretations which, in our opinion, emphasize the importance of detailed understanding of the hydrogeology and the hydrochemistry of the area in relation to both oil recovery operations and the possible environmental effects of these operations.

It has also been possible to outline the information which will be initially required for the acquisition of such an understanding.

Our summary of present knowledge of the groundwater flow systems and their possible effects is, as far as practical, arranged in ascending stratigraphic order.

The Precambrian rocks are generally impermeable and are considered to form an effective hydrostratigraphic basement.

The lowest formation of the Devonian, the La Loche Formation (Granite Wash) appears to be irregularly distributed in the area. It consists of arkosic debris and, in some locations, may be quite porous and permeable. It is known to range up to 130 feet in thickness. Rather vague evidence from old wells is interpreted as indicating the flow of water to surface from the La Loche Formation in one part of the McMurray area. For the most part, the La Loche is expected to be effectively sealed by the beds that overlie it. No severe regional problems are anticipated, although the strong hydrostatic head could cause local problems where vertical permeability exists. Locally, the La Loche might be considered for disposal of small quantities of toxic effluents but its limited distribution will probably prevent it being used for major disposal.

The La Loche is separated from the overlying Methy Formation by the generally impermeable McLean River Formation.

The porous, permeable, dolomitic Methy Formation (Keg River) is expected to present a major hydrogeological problem in the area. The formation is reefal in nature and, at least locally, has high porosities and permeabilities. In at least one area, the hydrostatic head in the Methy is known to reach almost to the surface, well above the base of the Oil Sands section.

Where the overlying Prairie Evaporite salt is present the Methy should be sealed, but where the salt has been removed by solution there may be vertical communication between the Methy and the Cretaceous McMurray. If this is the case, depressurization of the McMurray could permit access of highly saline Methy waters to the McMurray, and ultimately to the surface where severe environmental damage could occur. Such vertical access could also make dewatering of upper zones difficult. East of the Athabasca River, the Methy aquifers are probably being recharged from the east and the major flow system is probably westwards. West of the river, the direction of flow is not known.

The Methy is overlain by the Prairie Evaporite Formation, which consists predominantly of salt. Over part of the area the salt has been removed by subsurface solution, probably beginning shortly after deposition and interpreted as continuing to the present. East of the Athabasca River, much of the salt has been removed, although some outliers may still be present. To the west, the salt is thicker and less affected by solution but local solution lows may be expected. Where Prairie Evaporite salt is removed by solution, the overlying beds tend to collapse, often in a chimney effect which could result in very high permeabilities and could permit communication between the major Devonian Methy aquifer and the major Cretaceous McMurray aquifer.

We believe that earlier solution of salt has strongly affected the relative distribution of water-bearing and oil-bearing sections in the McMurray.

It has been stated that salt solution is probably still continuing and there is a strong possibility of future lowering of the present-day topographic surface in areas where this is taking place. Lowering is most likely west of the Athabasca River but the possibility cannot be eliminated in other areas.

The Prairie Evaporite is overlain by the Watt Mountain, generally impermeable, shale section. In the case of the Watt Mountain and all other overlying beds, permeability may be induced by collapse due to salt solution.

The Slave Point Formation overlies the Watt Mountain. The Slave Point is not generally permeable but there is some evidence of the local occurrence of porous and permeable beds. These could be more extensive than presently known.

For hydrogeological purposes, the Devonian beds overlying the Slave Point and comprising the Beaverhill Lake and Woodbend groups are combined in one hydrostratigraphic unit.

This unit is generally not permeable except where fractured.

Devonian waters are usually strongly saline, having obtained much of their salinity from solution of salt. Waters with a high calcium content may be present in the western part of the area but this has not been established.

The Devonian erosional surface, on which the McMurray was deposited, is very irregular due to the combination of erosional effects on the surface and karst-like effects produced by solution of the Prairie Evaporite salt. Where solution lows existed prior to McMurray deposition, the Lower McMurray aquifers are usually quite thick.

The upper part of the Devonian, near the unconformity, may be highly weathered and may form, locally at least, an important aquifer in connection with the McMurray aquifer.

Economically, the bitumen-bearing Cretaceous McMurray Formation is the most important unit in the area. There is frequently a water-bearing zone of variable thickness below the bitumen-bearing section. The water is under artesian pressure. Detailed mapping and testing will be required to determine how much continuity exists within the Lower McMurray aquifer. Knowledge of such continuity and the recharge rates of the aquifer will be extremely important in designing dewatering and depressurization operations. The recharge rates will also have a very important effect on choice and design of water disposal systems.

East of the Athabasca River, there is some evidence that the McMurray aquifer is being recharged from the vicinity of Muskeg Mountain but details are not known.

The chemistry, especially the chloride content, of the Lower McMurray water varies considerably. The water is usually relatively high in bicarbonate. There is some chemical evidence to indicate that the waters of the lower part have higher chloride salinities than those in the upper part. This may be due to vertical connection with the highly saline Devonian waters. If this is the case, extended pumping of the McMurray aquifer could increase the salinity of the water. McMurray waters to the west of the Athabasca River generally have a higher salinity than those to the east of the river.

The generally oil-bearing section of the McMurray also contains intra-McMurray aquifers. These are expected to be of limited thickness and extent, and major problems are not anticipated.

Gas is known to occur in the McMurray sands so that a four-phase system, consisting of a matrix, oil, water, and gas, exists, and this will complicate the hydrogeological and geotechnical analyses.

The McMurray is overlain by the Clearwater and Grand Rapids formations, which, although they contain aquifers, are not regarded as presenting severe problems.

The Pleistocene and Recent beds have not generally been given the attention they deserve during field operations. Important aquifers occur at and near the base of the Pleistocene. Meltwater channels were cut into the underlying bedrock surface. Some of these are filled with materials that have high porosities and permeabilities.

Post-McMurray waters are generally relatively fresh.

The Pleistocene and near-surface beds may contain local patches of permafrost, which could pose severe geotechnical problems.

Some small lakes and other low surface features could be due to post-Pleistocene salt solution and collapse of overlying beds. Other such features could form in the future.

We believe that the groundwater flow systems in the McMurray area offer a number of severe potential hazards to mining operations and the environment. One of the most important of these is the possible influx of highly saline Devonian waters into the upper aquifers and to the surface. The possibility of disrupting the natural base-flow systems to and from the Athabasca River, and related surface systems, through the formation of pits, tailings ponds, and other construction may be another difficult problem that industry has to face. Present and future flow systems will have a strong effect on engineering design. The safe disposal of waste water, some of which may be strongly saline, could be a major problem.

Although, because of their size, there is a tendency to concentrate on the effects of large open excavations, the groundwater systems could also be severely affected by in situ operations. Such operations will have to be designed with a full understanding of the regional and local groundwater flow systems.

A great deal of additional information will be required for an adequate understanding of the groundwater systems, their possible effects on operations, and the effects of operations on the environment. At present it is not possible to clearly define the information and analyses that will ultimately be required. A step-by-step process of data acquisition and interpretation is the most practical and economic approach to the problem.

1. INTRODUCTION

This report is based on a study authorized by the Oil Sands Environmental Study Group, hereinafter referred to as the O.S.E.S.G., in May 1974.

This volume reports on the following aspects of the study:

1) The determination of the present availability of pertinent and useful data on groundwater flow systems in the McMurray area.
2) The use of this information to make the best present interpretation of groundwater conditions and to outline the probable interacting impacts of the groundwater systems and oil recovery operations.
3) The laying of the foundations for the development of a "data bank" which will effectively handle the data to be expected in the future.

Other aspects, including recommendations, were treated in the original report.

The very limited reliable data available have severely restricted the analyses of the groundwater flow systems that can be made at present and this has precluded any complete definition of the data which will ultimately be required. Because the government authorities are commencing detailed work in the area including work on a data file, we have restricted our own work on such a file at this time to prevent duplication of effort and to allow for integration with future government data filing.

The team assembled for the project consisted of:

An Advisory and Review Committee comprising recognized Canadian experts in hydrogeology:

Dr. F. Farvolden, University of Waterloo

Dr. R.A. Freeze, P. Eng., University of British Columbia

Dr. W.A. Meneley, P. Eng., Saskatchewan Research Council

A group of Alberta consulting hydrogeologists:

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D. Currie, P. Geol., Mobile Augers and Research Ltd., Edmonton, Alberta

A project co-ordinator:

H.A. Gorrell, P. Geol., J.C. Sproule and Associates Ltd., Calgary, Alberta

During the project, contact was maintained with concerned government authorities, especially Drs. Toth and Hackbarth of Alberta Research and Dr. S. Smith of Alberta Environment, who co-operated fully.

The term 'groundwater' has been used in this report to include all water below the ground surface. The term 'hydrogeology' has been used as defined by Davis and DeWiest (1966) to mean "the study of groundwater with particular emphasis given to its chemistry, mode of migration, and relation to the geological environment."

From the Oil Sands operators' point of view, there are two closely interlocking aspects to groundwater problems in the McMurray area.

One involves the effects on the various groundwater flow systems on the many facets of oil recovery operations. These include, among others, the immediate hydrogeological and geotechnical problems related to pit development, the problems of waste disposal, effects of the systems on in situ recovery operations, and the need for adequate freshwater supplies for industrial and townsite use.

Equally important are the effects of recovery and related operations on the groundwater flow systems, and hence on the environment as a whole. These include possible changes in the water table, entry of salt water into subsurface or surface freshwater systems, changes in the flow and character of surface and subsurface water, and the development of new aquifers in tailings disposal areas.

In our work, we have attempted to keep a continual awareness of both of these aspects.

Considerable basic background information has been included in the report, especially with regard to groundwater concepts and definitions, although we have not attempted to repeat readily available published geological information. Much of the material presented will be common knowledge to many of the participants in the O.S.E.S.G., but we have felt that it was desirable to include it to provide the background for our discussions and recommendations and to emphasize the far-ranging effects of groundwater flow systems.

The report is illustrated by a number of cross sections, maps, sketches, and tables.

1.1 Approach to the Problem

The work was initiated through planning sessions involving the advisors, the consultants, and the co-ordinator.

The consultants visited the offices of the participating companies of the O.S.E.S.G. and reviewed available hydrogeological data.

Discussions were held with the staffs of the participating companies and copies of the most pertinent material were obtained for later study, integration, and analysis. Consultants also obtained pertinent material from Alberta Research and other sources.

The consultants collated and interpreted the available material to the extent that appeared practical and economic. There is very limited hydrogeological data available although the over 3,000 wells drilled have provided a great deal of geological information useful in more detailed studies. It was obviously impossible to analyze this detailed geological data in a first phase study.

2. GROUNDWATER FLOW SYSTEMS

A generalized discussion of groundwater flow systems and of their possible effects on Oil Sands recovery operations and the environment is presented on the following pages. This will provide certain basic information which should be useful for those readers who do not have a background in hydrogeology and will introduce some of the ways in which computer modelling may be used in groundwater studies. A more detailed description of present knowledge of the hydrogeology of the McMurray area is presented later in this report.

2.1 Steady-State Flow Systems

Groundwater in the upper few thousand feet of the earth's crust is always in motion (albeit very slowly in most cases). Under natural conditions (i.e., in those areas where groundwater is not being diverted in a major way by man), this groundwater motion occurs in large, three-dimensional, gravity flow systems. In such systems:

- Water enters the system in recharge or source areas by infiltration through the unsaturated zone to the water table or from surface sources.

- Water leaves the system in discharge or sink areas as evapotranspiration to the atmosphere or as base-flow to surface water systems.

- All water within the system can be considered to have been derived, at some time, from some point on the ground surface.

- Each particle of water within the system has the potential to move toward a system sink.
- The nature of the flow system is controlled by:
  (a) The distribution of fluid potential within the system. Where rocks are homogeneous and isotropic, this would be related to the water table and hence the topography.
  (b) The permeability configuration which is dependent on stratigraphy and structure of the three-dimensional geologic framework.

The existence of a three-dimensional flow field implies the existence of a three-dimensional potential field.

Flow always occurs away from regions of high potential to those of lower potential. In groundwater work, it is customary to refer to the potential at any point in terms of hydraulic head expressed as "feet of water above datum (usually sea level)" or more simply as "feet". The hydraulic head is usually determined in the field by measurement of fluid level in a piezometer or open pipe sealed into the flow system.

We will first consider the simplest possible case with uniform stratigraphy and permeability. In such a case, if the spatial distribution of the hydraulic head (the piezometric surface) can be determined, then a series of equipotential surfaces can be constructed and flow lines can be envisaged perpendicular to these equipotential surfaces.

In any two-dimensional cross section taken through a three-dimensional flow system, the equipotential surfaces become equipotential lines. An orthogonal set of equipotential lines and flow lines is termed a flow net. The analysis of flow nets is the basis tool of regional steady-state flow system analysis.

Figure 1 shows Hubbert's original diagram of a hypothetical gravity flow system in uniformly permeable material between two valley sinks (Hubbert, 1940). On this diagram, and on the other diagrams that follow, the dashed red lines are equipotential lines and the solid blue lines are flow lines. The flow field is a two-dimensional vertical section taken perpendicular to the direction of the flow of the streams that can be considered to be flowing in the valleys.

The recharge area is defined as that part of the system in which the net saturated flow of groundwater is directed away from the water table. The discharge area is defined as that part of the system in which the net saturated flow of groundwater is directed towards the water table. In general, uplands are recharge areas and valleys are discharge areas.

Figure 2a shows diagrammatically part of a hypothetical regional flow system in a cross section with more complex topography but still with uniform permeability. (To simplify the diagram, the water table is considered to be at the ground surface.)

Figure 2b shows the influence on the same system of a high permeability formation at depth (permeability 100 times that of the overlying material), and more closely approximates actual systems although it is still a very simple case.

Figure 2c shows a still more complex case with variations in permeability and dipping beds. Figure 2 is after Freeze (1962). Toth (1962, 1963) has published important studies on theoretical analyses of groundwater flow in small drainage basins.

Natural groundwater flow systems can be extremely complicated when topographic and geologic configurations and permeability variations are complex, as they normally are.

Figures 1 and 2 show hypothetical flow nets but, given the necessary measurements and geological data, it is possible to model groundwater flow systems for actual field locations.

Pits that bottom on or near the Devonian surface could be liable to buckling of the carbonate rocks under conditions of excessive fluid pressures.

Groundwater flow system analysis could provide initial estimates of fluid pressure regimes and hydraulic gradients to aid in the analysis of slope stability, piping, and buckling.

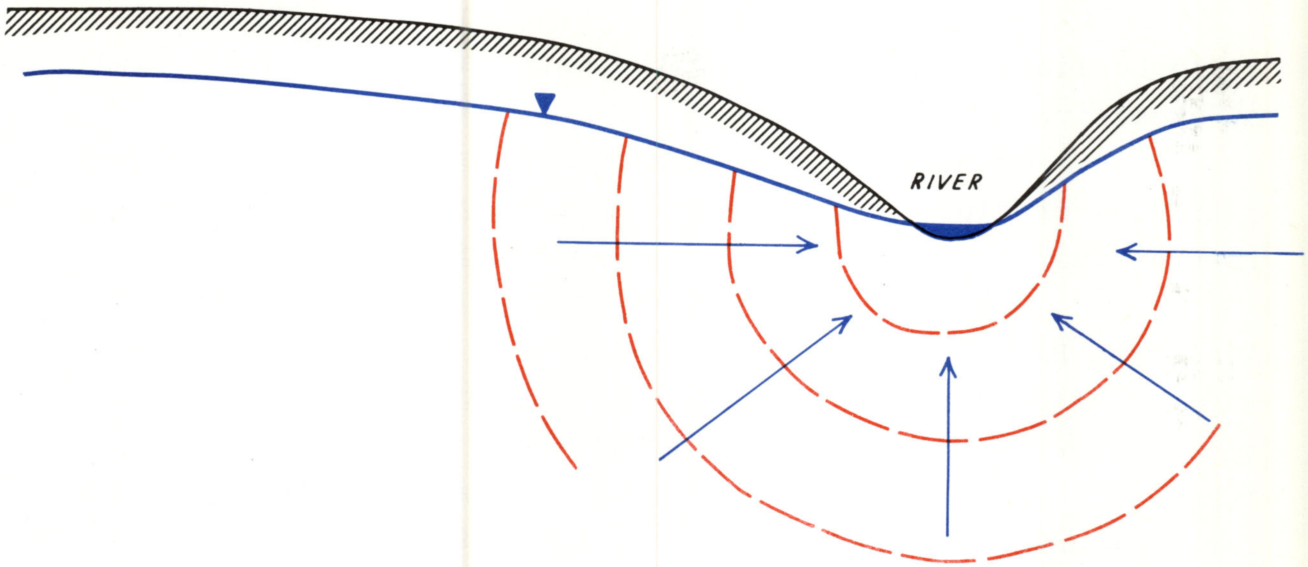
Many of the open pits will be located close to the Athabasca River. The Athabasca River is probably the natural major discharge area for the Oil Sands region. The natural groundwater flow system probably delivers base flow to the Athabasca along much of its length. This inflow is responsible for some unknown percentage of the total flow of the river. The natural system also delivers saline water from the Devonian which contributes to the salinity of the river water.

The introduction of open pits and the use of dewatering schemes will alter the natural quantity and quality of water entering the Athabasca in the vicinity of the pits (Figure 5).

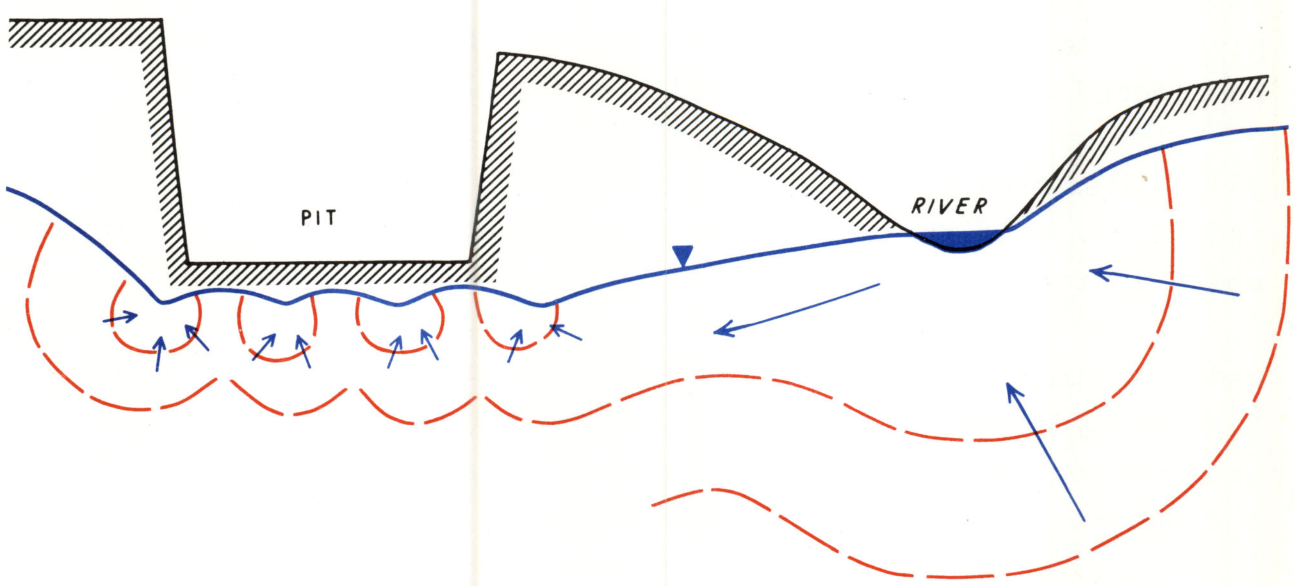
The quantity of natural base flow into the Athabasca could be reduced. If pit bottoms are below river level, groundwater flow could be induced from the Athabasca River towards the pits. The quantity of saline water reaching the Athabasca could be reduced and river salinities might decline.

On the other hand, dewatering could induce upward groundwater flow of saline Devonian waters to the pits or into the river. If the water enters the Athabasca, river salinities would increase.

The whole question of river flows and salinities under various developmental schemes requires detailed study. Further hydrogeological and hydrochemical studies of deeper groundwaters should aid in assessing the likelihood of saline inflows to open pits during dewatering.



a) NATURAL GROUNDWATER FLOW TO RIVER



b) POSSIBLE EFFECT OF DEWATERING ON GROUNDWATER FLOW

FIG. 5 EFFECT OF DEWATERING

approach. Use of the computer has the added advantage that sensitivity analyses can be more easily carried out by having the computer simulate several flow nets for the same geological and topographic configuration but using permeability values chosen from a range of permissible values.

In practice, neither the direct nor indirect approach should be used to the exclusion of the other because piezometric measurements are usually too sparse to allow sole reliance on the direct method and because geologic formations are usually too heterogeneous and permeability measurements too sparse to allow sole reliance on the indirect method.

A combination of the two approaches is more usual and the more practical.

For the combination approach, available data are collected on geology, permeability, and hydraulic head.

Drilling is carried out to add geological and hydrogeological information and to install piezometer nests. The piezometers are used to measure hydraulic head, to provide samples for chemical analysis, and to obtain permeability values by testing and measurement.

A back-and-forth, direct-indirect analysis is carried out, using all data. Permeability data and knowledge of geological framework are used to hypothesize the flow system by the indirect method. Piezometer data are used to check the interpreted flow system by the direct method.

There are also several field techniques that can indirectly assist in delineating groundwater flow. For example, the chemical composition of groundwater can be used as an interpretive tool, and natural vegetation, soil salinity, springs, seeps, flowing wells, and other types of surface evidence can provide valuable indications of underlying groundwater conditions.

Groundwater discharge to permanent streams can be estimated, using hydrograph separation or relationships between stream chemistry and stream discharge to distinguish base flow from the direct runoff component of stream flow.

Flow system analysis provides much more than just a qualitative picture of the groundwater flow. Accurate flow nets based on complete and reliable data can be analyzed quantitatively to provide valuable data for engineering and environmental studies including:

- Rates of groundwater recharge in recharge areas.
- Rates of groundwater discharge in discharge areas (including base flow to streams).
- Total quantities of steady-state flow through local, intermediate, and regional groundwater flow systems.
- Velocities of groundwater flow at any point in the system.
- Hydraulic head at any point in the system.
- Fluid pressures at any point in the system.
- Directions and rates of flow of pollutants.

Even when complete data are not available, flow net analysis can provide very useful qualitative interpretations.

2.2 Transient Flow Systems

When the activities of man result in the addition of water to or the removal of water from a steady-state regional groundwater flow system, a local transient groundwater flow system is set up in the vicinity of the activities during and following the period of addition or removal of water.

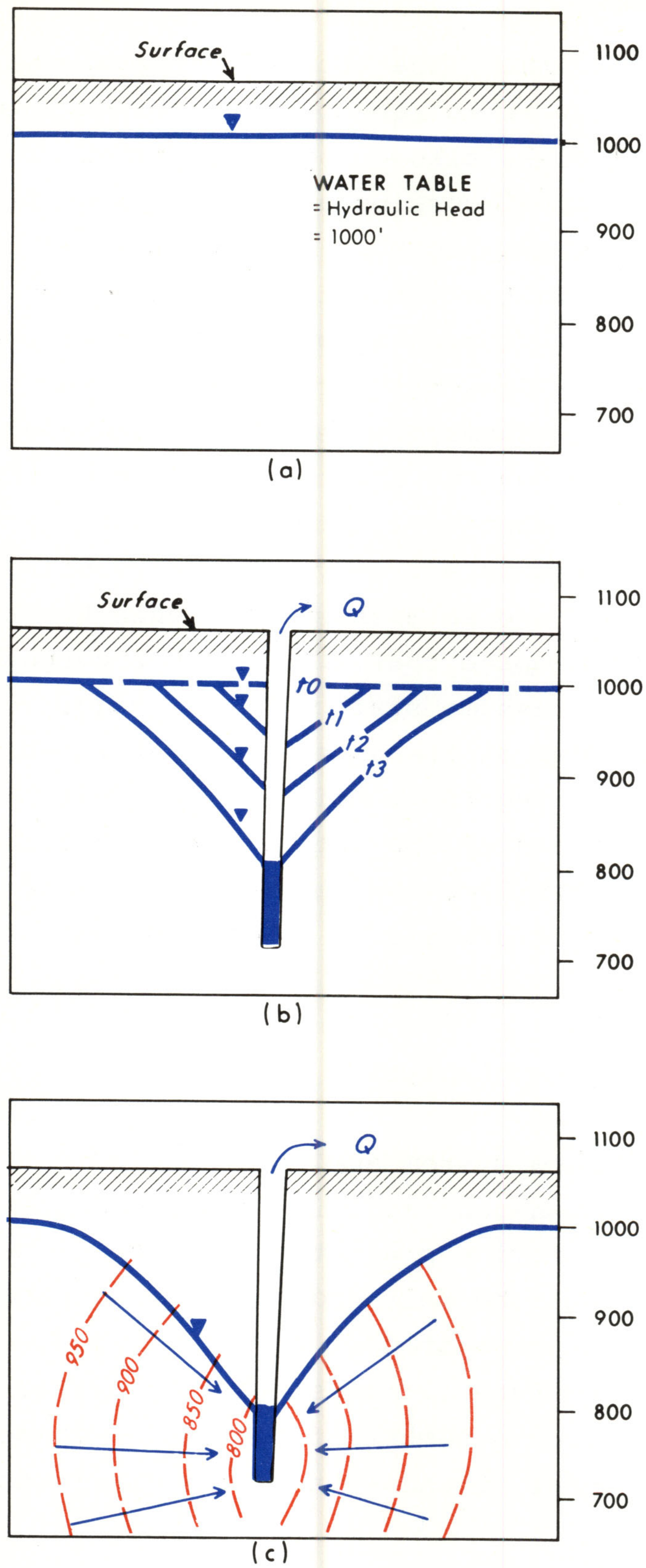
A transient flow system is one in which the hydraulic head patterns change in relatively short time periods. Under such conditions, the flow lines, the flow velocities, the fluid pressures, and the rates of inflow and outflow at the natural and man-made sources and sinks also change with time.

For purposes of discussion and example, we will consider briefly the commonest and most widely analyzed transient flow system, which occurs in the vicinity of a pumped well. Figure 3 shows schematically the drawdown in the water table with time (t) and the final flow net for a well pumping at a constant rate Q (gpm) from a homogeneous, unconfined aquifer. This diagram (Figure 3a) shows the situation when the initial conditions are regarded as static. Actually, transient flow is always induced at a point in a steady-state regional system but steady-state gradients are so much smaller than the transient gradients induced by the pumpage that, for present purposes, it introduces little error to assume static initial conditions. Figure 3b shows the drawdown in the water table at three time states (t_1, t_2, and t_3) during the pumping of the well. Figure 3c shows the flow pattern and equipotential lines of t_3. Similarly, much more complex flow system analyses may be carried out to determine the effects of removal or addition of water in different ways.

2.2.1. Transient Flow System Analysis

A transient flow system analysis carried out to predict the influence of man-made addition or removal of water on the regional system must provide predictions of the distance to which transient effects will be felt and the rate at which the transient effects will be propagated.

The extent and rate of transient flow system development is controlled by a number of factors. These include the initial regional, steady-state flow gradients,



HYDRAULIC HEAD PATTERN AT *time 0 = t0*

WATER TABLE DRAWDOWN AT *t1, t2, & t3*

FLOW PATTERN AT *t3*

FIG. 3 DRAWDOWN IN A WELL PUMPED AT RATE *Q*

Computer simulation is a valuable tool in the analysis of transient flow systems but there are computer limitations that restrict its use.

2.3 Implications for Development and Environmental Change

Many of the engineering schemes that are part of the proposed development systems in the Oil Sands will lay considerable stress upon the steady-state regional groundwater flow system and will cause transient alterations in this system. Among these are the introduction of open pits, dewatering of open pits, the use of tailings ponds, the growth of tailings mounds, the possible deep well injection of waste water, and the in situ extraction of oil. The following sections briefly discuss these items in turn, with emphasis on the types of groundwater-oriented geotechnical problems that may be encountered and the predictive transient analyses that might prove beneficial. Many of the oil recovery plans also have hydrologically connected environmental implications and these too are noted.

2.3.1. Open Pit Mining and Dewatering

The introduction of open pits in the Oil Sands region will stress the natural hydrogeologic system.

The pits that are envisaged are large enough that their presence will constitute a significant change in the surface topography, and this will induce changes in the topography of the water table and in the flow systems.

If the pit bottoms are below the present water table, water inflows are to be expected. Perhaps the most serious mining obstacle that could be encountered in the proposed operations would be flows so large that they prohibited excavation the variabilities in the addition or removal of water, the geometry of the sources or sinks (that is, one well, many wells, ponds, etc.), and the three-dimensional configuration of the permeability, porosity, and compressibility of the geological materials in the vicinity of the source or sinks.

For the special case of groundwater pumpage from a horizontal, confined aquifer, these three fundamental grounds of parameters are often combined into two parameters, the transmissibility and the storage coefficient, which are defined later in the text. These terms have less meaning in unconfined aquifer pumpage and no meaning for some other flow systems.

The schematic diagram shown in Figure 3 is the simplest possible case. The response to pumping in an actual three-dimensional system with complex geological stratigraphy can be much more complicated.

As with the steady-state flow system analysis, there are essentially two approaches to the analysis of transient groundwater flow in the field. These are the direct method of field measurement of the time-dependent hydraulic head changes in piezometers and the indirect method of theoretical flow system analysis based on measurements of the permeability, porosity, and compressibility of the geologic formations.

Only the indirect method can be used as a predictive tool for design purposes. In these cases, the direct method is usually assigned the role of a monitoring technique to assess the reliability of the design analysis. Initial field efforts, therefore, emphasize the determination of permeabilities, porosities, and compressibilities of the geologic materials in the vicinity of the anticipated transient flow field. Knowledge of the pre-transient, steady-state system upon which the transient system will be superimposed is essential and this is best obtained by a combination of direct and indirect methods.

under dry conditions. Such flows would be most likely from cavernous Devonian carbonates. The presence of porous Devonian beds has been established but the hydrodynamics within these beds are not yet known. Evidence is available that, locally at least, hydraulic heads in the McMurray Formation and in the Devonian section are several hundred feet above the base of the Oil Sands.

The pits may provide a man-made discharge area that could alter the flows to the natural discharge area (probably the Athabasca River).

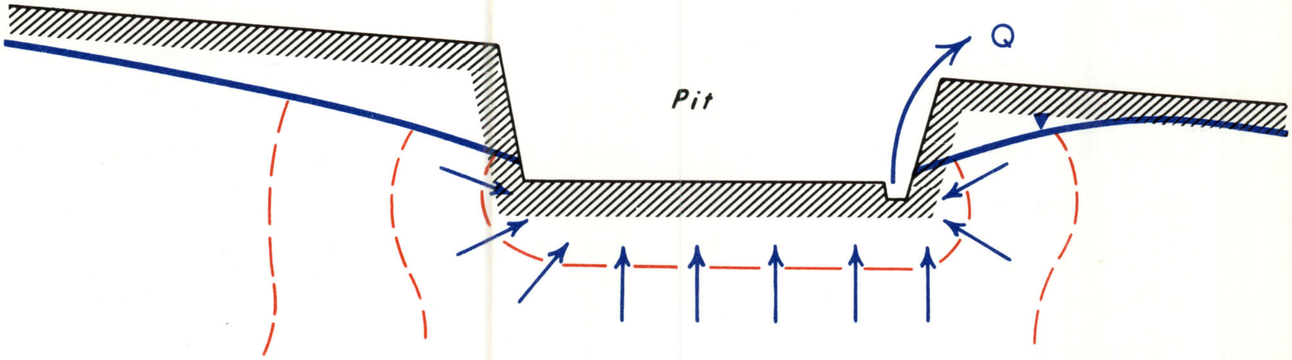
An initial estimate of the groundwater inflows to be expected in various hydrogeological settings could be provided by steady-state regional groundwater flow system analysis.

Dewatering of the pits will further stress the groundwater system. Figure 4a shows, diagrammatically, a passive dewatering control scheme. Figure 4b shows an active dewatering control scheme. Passive control would allow water to flow into the pits with pumping being carried out from a sump area. Active control would involve a dewatering scheme utilizing a series of wells placed ahead of the pit face or around the pit. Transient flow system analyses could be used to predict the growth and expected zone of influence of such dewatering systems.

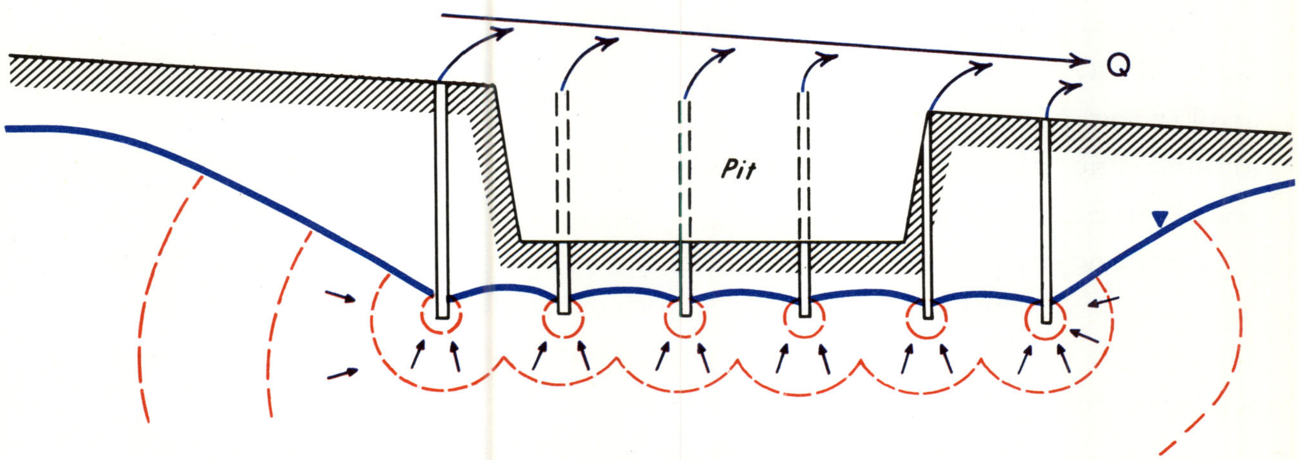
There are several geotechnical problems closely linked to groundwater conditions that could arise in open pit operations.

The slope stability of the pit faces depends on the fluid pressures (pore pressures) of the groundwater at the pit slopes and for some distance behind and below the face.

Pits that bottom within the McMurray sands may have piping problems. An analysis of piping requires knowledge of the hydraulic gradients below the pit floor.



a) Passive System



b) Active System

FIG. 4 DEWATERING CONTROL SYSTEMS

Pits that bottom on or near the Devonian surface could be liable to buckling of the carbonate rocks under conditions of excessive fluid pressures.

Groundwater flow system analysis could provide initial estimates of fluid pressure regimes and hydraulic gradients to aid in the analysis of slope stability, piping, and buckling.

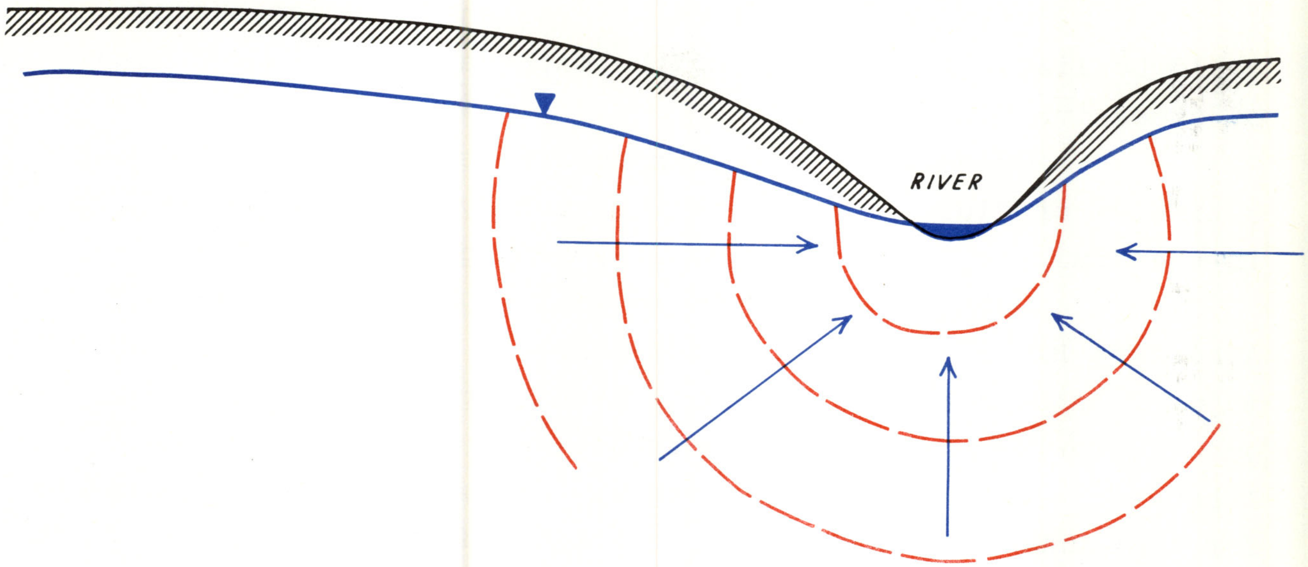
Many of the open pits will be located close to the Athabasca River. The Athabasca River is probably the natural major discharge area for the Oil Sands region. The natural groundwater flow system probably delivers base flow to the Athabasca along much of its length. This inflow is responsible for some unknown percentage of the total flow of the river. The natural system also delivers saline water from the Devonian which contributes to the salinity of the river water.

The introduction of open pits and the use of dewatering schemes will alter the natural quantity and quality of water entering the Athabasca in the vicinity of the pits (Figure 5).

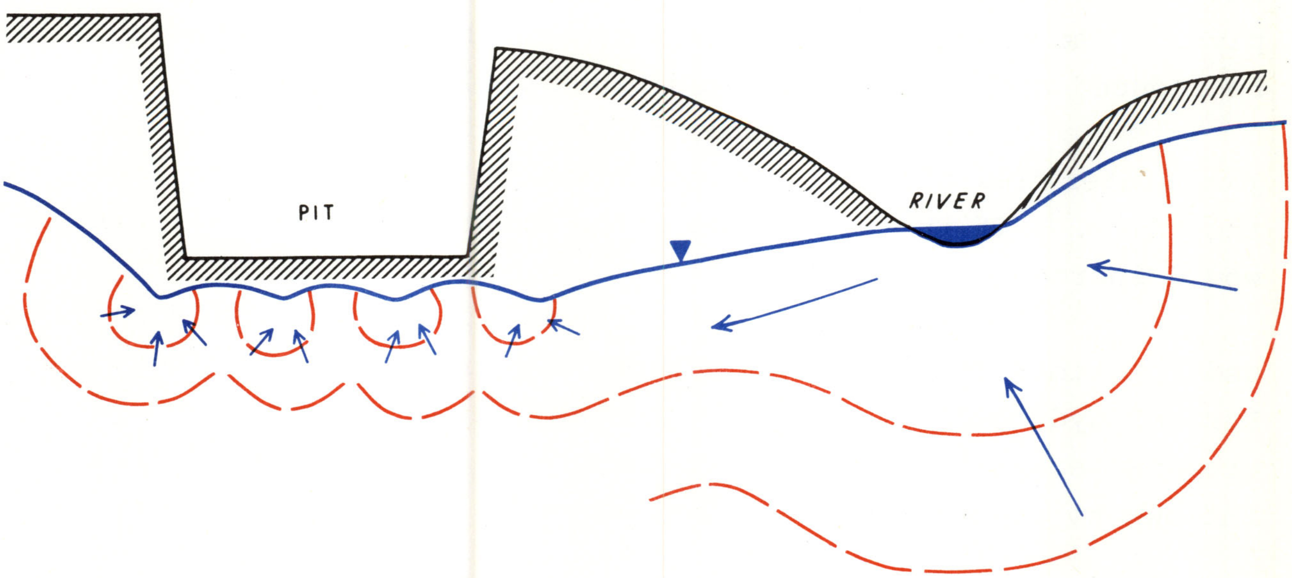
The quantity of natural base flow into the Athabasca could be reduced. If pit bottoms are below river level, groundwater flow could be induced from the Athabasca River towards the pits. The quantity of saline water reaching the Athabasca could be reduced and river salinities might decline.

On the other hand, dewatering could induce upward groundwater flow of saline Devonian waters to the pits or into the river. If the water enters the Athabasca, river salinities would increase.

The whole question of river flows and salinities under various developmental schemes requires detailed study. Further hydrogeological and hydrochemical studies of deeper groundwaters should aid in assessing the likelihood of saline inflows to open pits during dewatering.

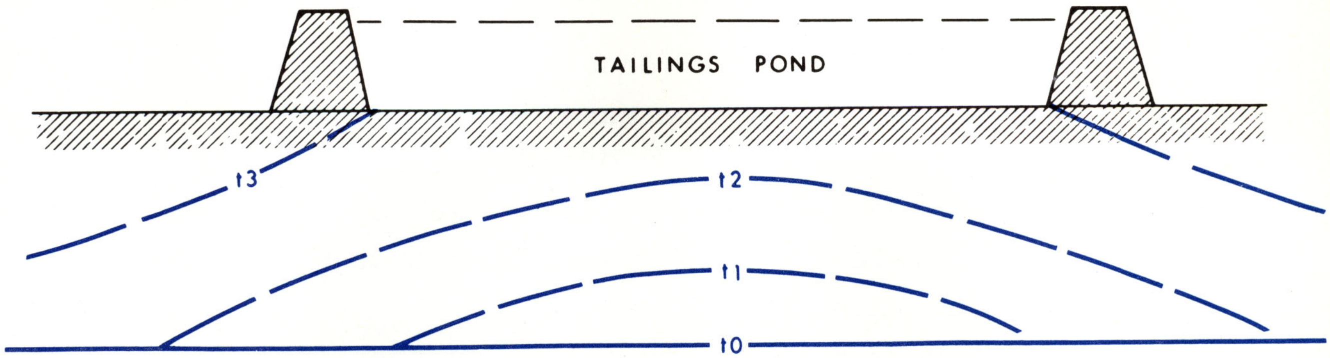


a) NATURAL GROUNDWATER FLOW TO RIVER

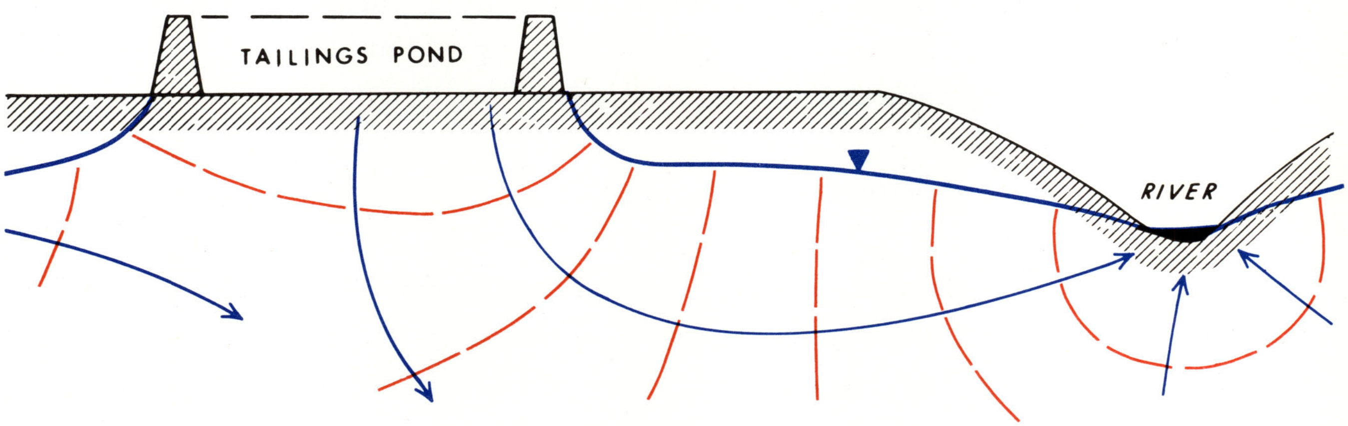


b) POSSIBLE EFFECT OF DEWATERING ON GROUNDWATER FLOW

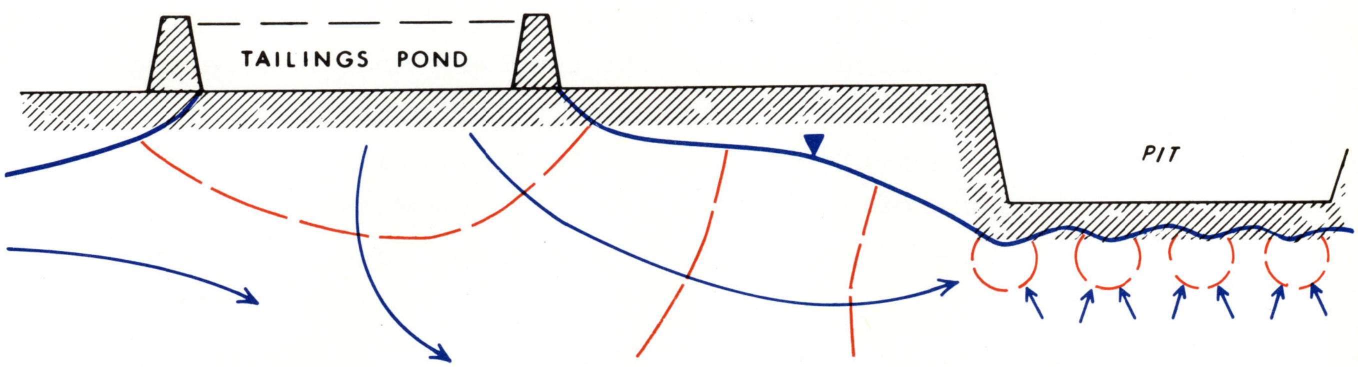
FIG. 5 EFFECT OF DEWATERING



a) GROWTH OF GROUNDWATER MOUNDS BELOW TAILINGS POND



b) POSSIBLE EFFECT OF TAILINGS POND ON GROUNDWATER FLOW SYSTEM



c) POSSIBLE EFFECT OF TAILINGS POND ON PIT DEWATERING

FIG. 6 EFFECTS OF TAILINGS PONDS

Disposal of water produced in dewatering operations poses its own problems which increase with the quantity and salinity of the produced water. Of course, it will not be possible to dispose of significant quantities of saline waters into the surface systems. The disposal of such water is briefly discussed later in this section.

It may be possible to establish that specified amounts of water can be disposed of into the Athabasca River system without environmental damage.

Saline waters discharge naturally into the Athabasca River system and a detailed analysis of the geology, and chemistry of local and regional flow systems could help determine whether water produced in dewatering operations is water that would have entered the Athabasca River in any case.

2.3.2. Tailings Ponds

The extensive use of tailings ponds at extraction sites will affect the groundwater system in a manner which, in general, will be the opposite of the effect of the dewatering schemes.

Tailings ponds will lead to the growth of groundwater mounds beneath the ponds (Figure 6a). They will form a man-made recharge area that will alter the flow to nearby natural or man-made discharge areas. If tailings ponds are placed near the Athabasca River, flow could occur from the tailings ponds towards the river (Figure 6b). If they are near dewatering pits, flow may be induced from ponds to the pits (Figure 6c).

If the permeabilities of near-surface formations are high, the zone of influence from a groundwater mound could extend over a considerable distance, perhaps several miles.

The use of semi-impermeable liners on the bottom of tailings ponds (or the formation of low permeability zones by the settlement of "fines") can reduce downward seepage but cannot stop it. For the size of tailings ponds envisaged in the developmental schemes in the Oil Sands region, the quantity of groundwater outflow from the ponds would still be large.

There is a danger that water from tailings ponds will sooner or later appear in pit dewatering systems or as seepage to the surface.

Seepage through dykes could not only allow the water to reach surface but could also threaten the integrity of the dykes.

The growth and effect of groundwater mounds induced by tailings ponds and other possible effects can be studied with transient flow systems analysis provided that sufficient data on regional and local flow systems are available.

2.3.3. Sand Mounds

Allen and Sandford, in their description of the Great Canadian Oil Sands operation in the Alberta Research "Guide to the Athabasca Oil Sand Area" (Carrigy and Kramers, 1973), estimate the overburden swell factor of tailings at 35 percent. They suggest that a worked out lease could have a land surface over 100 feet higher than the original topography.

The amount of probable reclaimed land surface is large enough that the presence of the mounded topography will constitute a significant change in the regional surface topography. It is likely that higher water tables will be induced in the tailings mounds. Presumably the tailings mounds will be mainly sand and may have higher porosities than those of McMurray sand in place.

If groundwater mounds develop in the high permeability sand mounds, then they may become recharge areas and this may result in higher natural flows of high quality water to the Athabasca River or into the subsurface.

Sand mound construction and the resulting growth of water table mounds may lead to springs, seeps, piping, and slope-stability problems on the mound slopes.

We understand that studies of the best methods for rehabilitation of spoil piles of sand are underway but we should emphasize that the problem is much more significant than the mere establishment of vegetative cover. The total hydraulic response of this region will, in the future, be influenced mainly by the configuration and the properties of the materials within the spoil piles. It should be quite feasible to design the terrain to suit some future need or purpose. For example, it should be possible to design a terrain with gently rolling uplands drained by permanent streams which have very little storm runoff and thus flow almost continuously with clear cold groundwater, perhaps ideal for trout. On the other hand, rather large hills of sand with uplands and plains could be developed and perhaps used for the disposal of certain sorts of wastes in thick, unsaturated zones. The configuration, texture, moisture content, compaction, stratification, and minor constituents of the sand spoil are factors in determining the future hydrologic regime of the region.

When more data are available, a steady-state regional groundwater flow analysis of the post-development regime, taking into account the changes in the water table and permeability configurations due to tailings mounds, could be carried out to assess the ultimate long-term effects of development on the hydrogeologic regime. Special attention would be paid to the original and final inflows to the Athabasca in terms of quantity and quality. The new distribution of recharge and discharge areas would also be studied because discharge areas other than the Athabasca may have environmental importance as wetland areas.

2.3.4. Deep Well Waste Water Injection

The deep well injection of waste water, or water removed in dewatering operations, to the subsurface may be a component of some developmental plans. From present information, the Devonian section appears to be the most favourable for injection.

Deep well injection raises fluid pressures and hydraulic heads at the point of injection. It creates a man-made source at depth and produces a transient flow system that alters the natural regional groundwater flow system.

The storage capacity of geological formations is a limited natural resource, re-usable under some conditions but not after the disposal of toxic wastes.

The volume of waste that can be injected under safe injection conditions is limited to that which can be provided by compression and displacement of original formation fluids, and by compression of the formation rock. This represents only a part of the aggregate pore space. Waste injections may displace formation waters (usually saline) which ultimately reach the surface.

Subsurface disposal of waste does not constitute permanent disposal in the strictest sense of the word; rather it detains waste in transitory storage. It may lead to irreversible pollution of the subsurface environment.

Waste injected into the subsurface would enter a flow system whose ultimate discharge area is probably the Athabasca River. Flow could be pushed in this direction under higher gradients than exist in the present natural flow systems. It is not inconceivable that injected waste could reappear in the Athabasca River at some future date, even long after injection had been discontinued. Prior to this, the natural flow of formation waters could be increased due to their displacement by the injected fluids. It is quite possible that injection of moderately saline water into the subsurface could increase the outflow of water of a higher salinity because of displacement.

Excessive injection pressures have been known to cause earth tremors.

Deep well waste injection systems must be designed with the aid of prediction models that include consideration of chemical diffusion and reactions and hydrodynamic dispersion as well as the usual convective groundwater flow. The use of numerical mathematical methods and digital computer solutions for such problems is presently in the research stage and further basic studies will be required to develop practical methods.

At present, we do not have enough information to predict, even within one or two orders of magnitude, the amount of water which may have to be disposed of.

The chemical compatability of injection water with formation water and the rocks must be considered to avoid any reduction of porosity and permeability.

2.3.5. In Situ Extraction

The widespread injection of fluids into the McMurray Formation for purposes of oil extraction will place a major stress on the hydrogeological environment.

The pattern of injection and production wells set up for the injection process will produce a complex transient flow system, altered fluid pressures, and hydraulic heads that will influence the natural regional groundwater flow system.

Depending on the geometry and efficiency of the well pattern, it may have the overall effect of a source or a sink in the regional system. If perfectly designed, it would, of course, be hydraulically neutral.

The heat flow effects may spread further than the effects on the hydrodynamic system, as groundwater is an effective conductor of heat. Increase of temperatures of base flow to the Athabasca would be of environmental importance. If temperatures of groundwater are raised significantly on a regional scale, this would constitute a form of thermal pollution.

If careful control is not exercised, oil-rich hot waters may escape from the injection site and pollute those aquifers that may have economic importance as sources of water in the future.

The injection of solvents as an extractive process would have the potential of creating widespread subsurface pollution more serious than the thermal pollution created by hot water injection.

Where overburden thicknesses are not great, excessive hot water injection pressures could cause piping to surface, blowouts, and deformations of earth materials.

As oil is removed from the sand by the hot water, the permeability of the sand will increase causing major changes in the flow systems. The usual analytical techniques of reservoir prediction and groundwater flow analysis are not designed to cope with transient systems in which the geologic parameters themselves change with time. New analytical techniques would have to be designed to assess the impact of oil removal on the regional and local flow systems.

Very thorough analysis of the possible physical and chemcial effects of in situ recovery operations will be required. A thorough and detailed knowledge of present groundwater flow systems, both local and regional, will be required before such analyses could be carried out.

3. GROUNDWATER TERMINOLOGY

Because this report is expected to be used by technical staff with backgrounds largely in the petroleum industry as well as by those with hydrogeological experience, and because the terminologies used in these two fields are somewhat different, we believe that certain definitions and discussions, in addition to those previously given, are essential to avoid any possibility of confusion.

The concepts of fluids flow in porous media used by the petroleum industry and those used in groundwater studies both stem from Darcy's law but, to some extent, the concepts and terminology have evolved independently.

Within the broad field of hydrogeology, there has been a natural tendency to specialization, with some workers concentrating on theoretical aspects, especially as applied to regional flow in larger basins, while others have emphasized the more detailed local geological control of water flow.

We believe that all aspects are important to a thorough knowledge of groundwater systems. The McMurray area, because of the economic scale of the recovery projects, the potential water problems, and the opportunity to involve specialists with widely divergent backgrounds, offers a unique opportunity to apply different technologies in a co-operative manner to the solution of pressing hydrogeological problems.

This co-operation is particularly important in the McMurray area where some fluid systems involve four phases (matrix, bitumen, gas, and water) as opposed to the two- or three-phase systems usually involved in groundwater studies (Hardy and Hemstock (1963).

3.1 Definitions

An aquifer (reservoir) may be defined as a saturated geologic unit which yields water in significant quantity. Groundwater occurs in aquifers of various lithologies.

The accompanying diagram (Figure 7) illustrates different aquifer types in terms of the relative permeability of the aquifer and the confining beds (caprock).

The most simple case is shown in Figure 7a, and is termed the unconfined aquifer. In nature, the closest example would probably be a partially saturated sand dune. The water level in wells completed into the unconfined aquifer is a true water table or phreatic surface. A phreatic surface is a free water surface open to the atmosphere. When the water table declines, gravity drainage of the pore spaces occurs.

Figure 7b illustrates the confined aquifer where the permeability of the confining layer (caprock) is considered to be zero. Water levels in wells completed in a confined aquifer define a piezometric surface, and if the well is used only for measuring water levels it is known as a piezometer. The confining bed in this illustration is also known as an aquiclude -- a saturated bed through which there is no appreciable movement of water. Figure 7b illustrates the artesian aquifer as one in which groundwater is confined under pressure and water levels in wells rise above the top of the aquifer.

The remaining two cases in Figure 7 show the most probable situations in nature. Most confining beds will allow some leakage in and/or out of the aquifer which they confine. This leakage through confining beds has led to the use of the term aquitard, which can be defined as a saturated geologic unit of low permeability that yields limited quantities of water to drains, wells, springs, and seeps compared to an

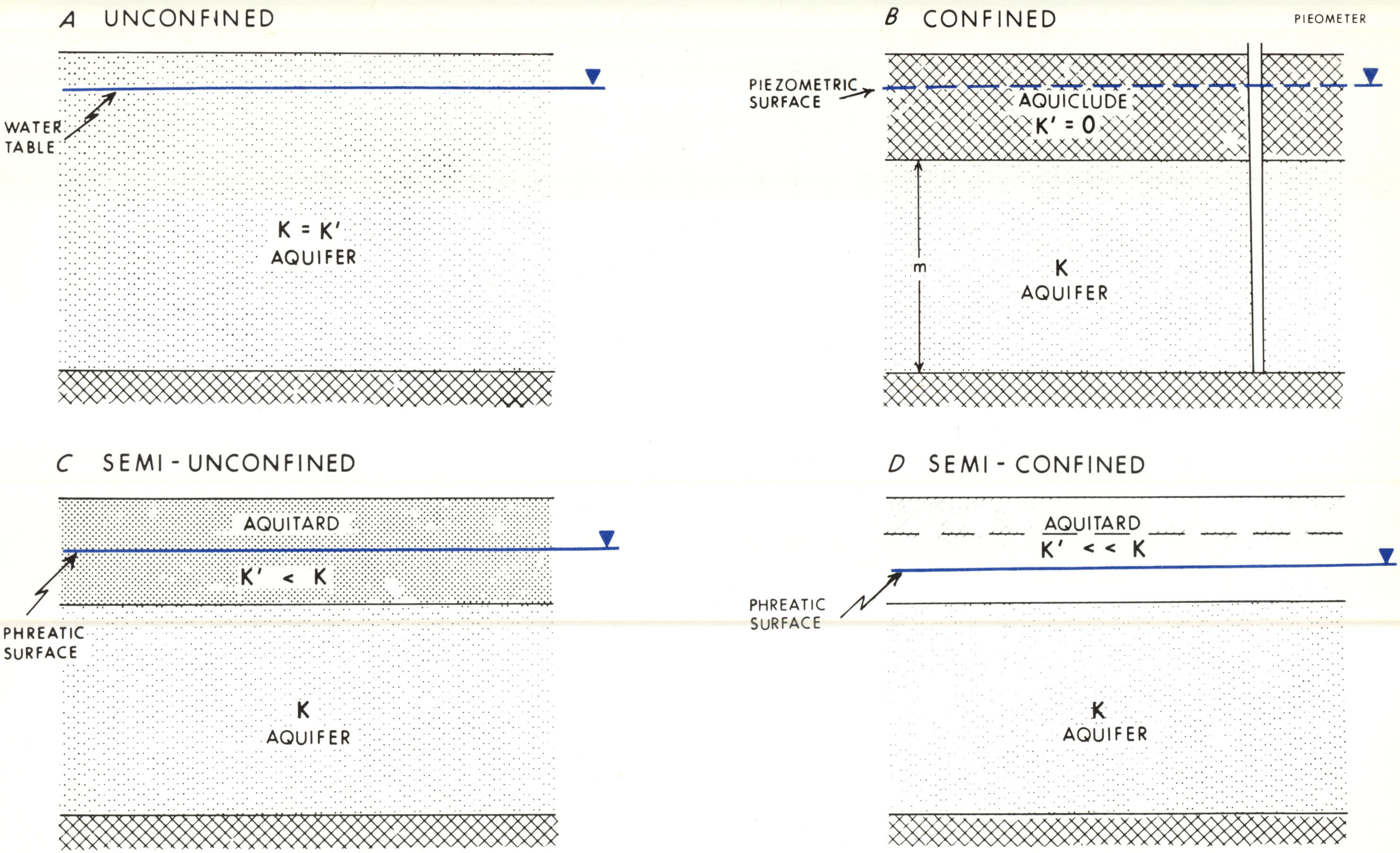


FIG. 7 DIFFERENT AQUIFER TYPES

aquifer but through which significant leakage of groundwater is possible.

Determination of the confined or unconfined condition of aquifers is vital to an understanding of the nature of the regional groundwater flow systems, and in pump test evaluations.

In confined aquifers, a loss of hydraulic head propagates quickly because the release of water from storage is entirely due to the compressibility of the aquifer material and that of the water. Figure 8 illustrates the forces acting at an aquifer interface. S_t is the total load acting on the aquifer. S_k is the load borne by the aquifer matrix. S_w is the load borne by groundwater in the pore space. If S_w is reduced, the load borne by S_k increases and there is a distortion of the aquifer skeleton. Therefore, the loss of hydraulic head can be measured over relatively great distances.

In unconfined aquifers, the propagation of head loss is rather slow because release of water from storage is mostly due to dewatering of the zone through which the water is moving. Consequently, head losses cannot be measured over great distances unless withdrawal of water is continued over a long period of time.

Semi-confined and semi-unconfined aquifers exhibit an intermediate condition.

The co-efficient of permeability (K) is a measure of an aquifer's capacity to transmit groundwater. Opening (a) in Figure 9, taken from Ferris (1962), helps to visualize the definition by Meinzer (1928) of the co-efficient of permeability as the rate of flow of water, in gallons per day, through a cross sectional area of one square foot, under a hydraulic gradient of one foot per foot at a temperature of 60°F.

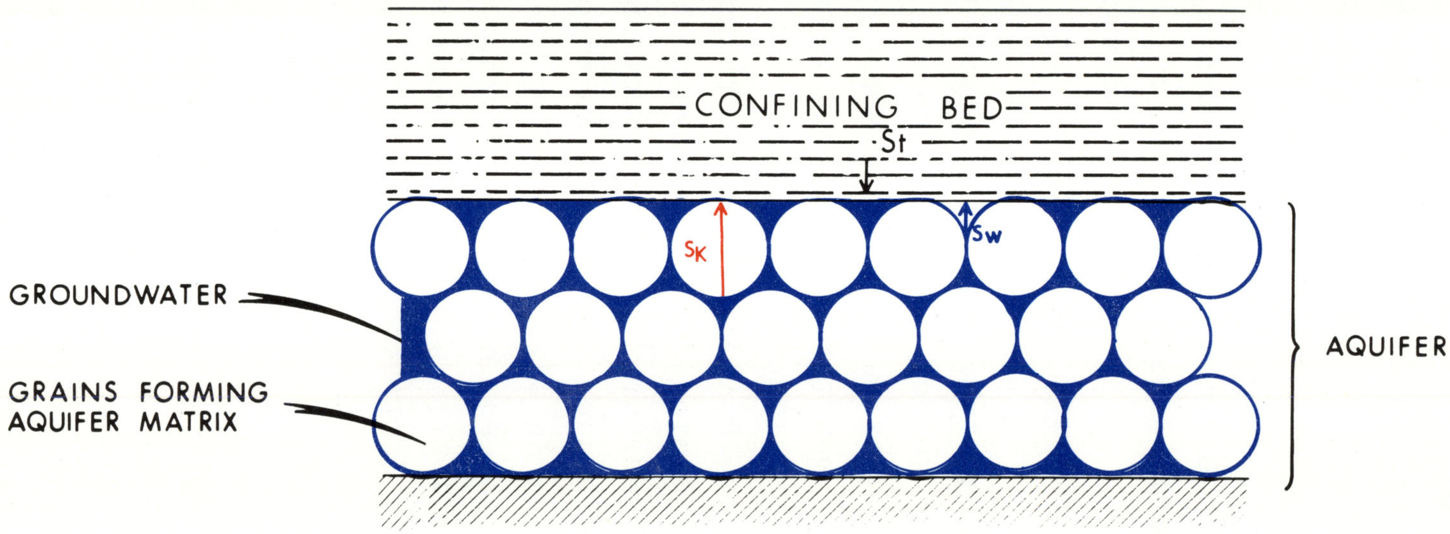


FIG. 8 EXAGGERATED VIEW OF FORCES ACTING AT INTERFACE BETWEEN ARTESIAN AQUIFER AND CONFINING MATERIAL

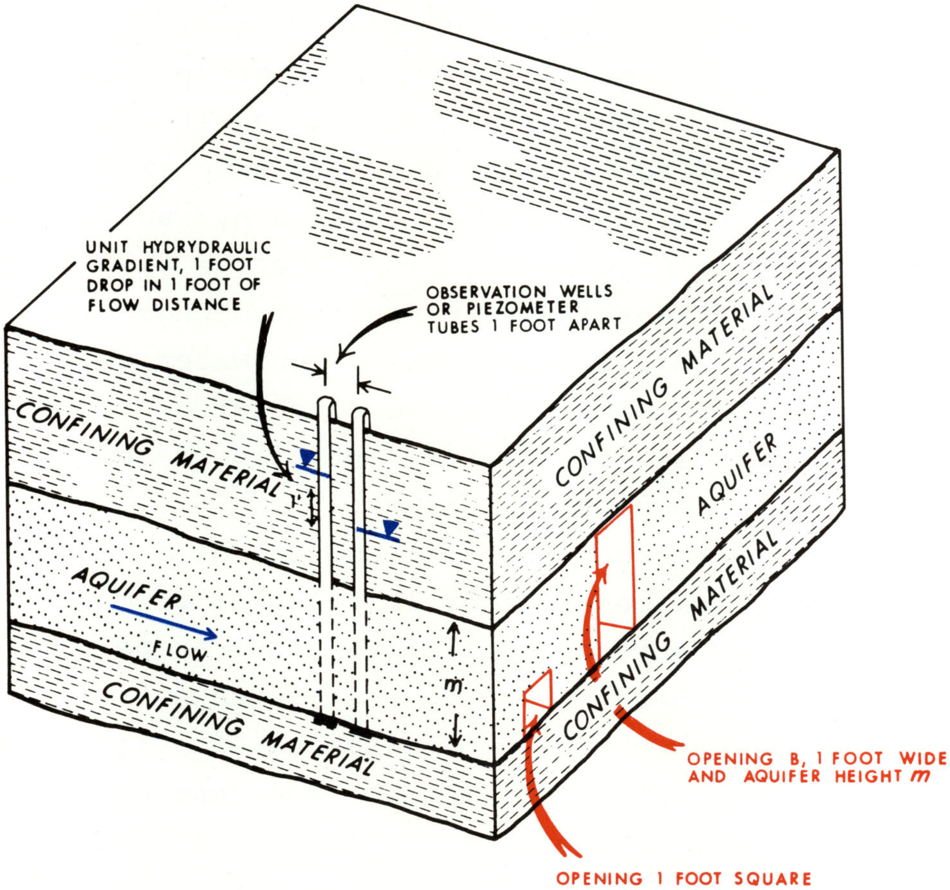


FIG. 9 DIAGRAM ILLUSTRATING COEFFICIENTS OF PERMEABILITY & TRANSMISSIBILITY

(AFTER FERRIS ET AL 1962)

Determination of the co-efficient of permeability in groundwater terms is based on pump testing the aquifer for various lengths of time and analysis of the measured water level drawdowns and recoveries.

The co-efficient of transmissibility (T) was defined by Theis (1935) as the rate of flow of groundwater, at the prevailing water temperature, in gallons per day, through a vertical strip of the aquifer one foot wide extending the full saturated height of the aquifer under a hydraulic gradient of 100 percent. In Figure 9, it would be the flow through opening b. (The term 'transmissivity' is interchangeable with transmissibility.) This is the usual groundwater unit from which reserve or safe pumping rates are calculated. Expressed simply, transmissibility is the co-efficient of permeability multiplied by the saturated aquifer thickness.

The storage co-efficient (S) of an aquifer is defined as the volume of water it releases from or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. It is expressed as a dimensionless number. Storage co-efficient refers only to the confined parts of an aquifer and depends on the elasticity (compressibility) of the aquifer material and the fluid. The storage co-efficient usually has an order of magnitude of 10^{-3} to 10^{-6}.

Specific yield is often used interchangeably with storage co-efficient, although, strictly speaking, specific yield refers to the unconfined parts of an aquifer. In practice, it is considered equal to the effective porosity. Specific retention (which may be compared with residual oil saturation) plus specific yield should equal porosity.

The pumping rate (Q) is the rate in gallons per minute at which the supply well is being pumped.

The safe pumping rate (Q_{20}) is designated by the upper case letter Q with a 20 subscript and is in common use in Alberta. It was defined by Farvolden in a presentation to the Alberta Water Well Drillers Association and can be calculated from the Jacob (1949) modification of the Theis pump test formulae. It can be expressed as

$$Q_{20} = \frac{TH}{2,110}$$

where T = transmissibility in Imperial gallons per day per foot

H = total available drawdown or the depth from the non-pumping water level in the well to the top of the aquifer.

The hydrostratigraphic unit consists of rocks with similar groundwater transmission properties. Hydrostratigraphic units may or may not coincide with classic stratigraphic units.

4. SUMMARY OF HYDROGEOLOGICAL DATA HELD BY OPERATORS

One of the major objects of the present assignment was to determine and summarize the present availability of pertinent hydrogeological data for the McMurray area. This was accomplished by visiting the offices of each of the member companies of O.S.E.S.G. to determine what information they held which would be pertinent to this study or to more detailed future groundwater studies. The co-operation of the members of O.S.E.S.G. was very good, and they freely made information available to the consultants and permitted them to make use of the material which was particularly pertinent to the present study. Time and economic restraints naturally precluded a detailed study of all the information available.

Table 1, which is presented on the following page, summarizes the pertinent information available. The table is largely self-explanatory but some comments may aid in its interpretation.

Column 3 indicates the total holes drilled by individual companies on their leases.

Column 4, 5, and 6 indicate the quality of logs run on these holes. Column 4 indicates the number of holes with high quality logs, meaning tools which have resistivity devices capable of detecting thin beds and which also have adequate porosity logs. Column 5, headed "Holes with Single Point Logs", indicates the number of holes which, in our opinion, have logs which are less than adequate for detailed interpretation. They are normally single point resistivity devices. We cannot recommend this type of log for holes which are to be used for any hydrogeological interpretation. Column 6 indicates the

TABLE 1

SUMMARY OF HYDROGEOLOGICAL DATA HELD BY OPERATORS

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
			Holes With			Holes											
Company	Lease No.	Total Holes	High Quality Logs	Single Point Logs	No Logs	To Top of Devonian	Into the Devonian	Water Analyses	Measured R_w	Drill Stem Tests	Measured Water Levels	Pump Tests	Top of Devonian Map	Water Sand Isopach	Cross Sections	Piezometers	Remarks
Shell	13	400	400	-	-	360	4	40	240	-	Yes	4	Yes	Yes	Yes	Yes	Long pump tests
Syncrude	17	700	100	25	575	600	2	20	-	Yes	Test Pit	2(?)	Yes	Yes	Yes	Yes	
Syncrude	29	30	20	-	10	-	-	-	-	-	-	-	Yes	-	-	-	
Syncrude	31	20	20	-	-	-	-	-	-	-	-	-	Yes	-	-	-	
Amerada	88,89	145	5	140	-	120	-	5	-	-	6	-	Yes	-	Yes	-	Several flowing holes
Ashland	19	50	50	-	-	-	2	1	-	4	-	-	Yes	-	Yes	-	Pacific operates lease
Home	30	145	25	113	7	145	-	24	42	-	4	1	Yes	Yes	Yes	Yes	2-hour pump test
H.B.O.G.	18	115	100	-	15	90	-	1	1	-	-	-	Yes	Yes	Yes	-	
Fina	12,34	169	41	-	128	34	1	25	-	-	Yes	1	-	-	Yes	Yes	
Fina	6,33	142	29	-	113	-	-	-	-	-	-	-	-	-	-	-	
Aquitaine	39	19	19	-	-	12	-	-	-	-	-	-	-	-	-	-	Elevations on Devonian
Tenneco	87	73	57	16	-	73	-	1	-	-	Yes	1	-	Yes	Yes	Yes	Good pump test
Chevron	23	160	110	40	10	110	-	-	-	-	-	-	Yes	-	Yes	-	Plus fee lots
Texaco	49,51	33	16	16	1	30	2	2	2	2	-	1	-	-	-	-	Elevations on Devonian
Amoco	73,76	85	85	-	-	85	1	12	-	-	-	-	Yes	-	Yes	Yes	
Union	23	35	15	20	-	15	-	-	-	-	-	-	-	-	-	-	
Pacific	19	160	54	106	-	65	2	1	-	4	-	-	Yes	-	-	-	
Total	50	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	No information
Husky	35	35	35	-	-	34	-	-	-	-	-	-	Yes	-	-	-	
B.P.O.G.	24	154	154	-	-	154	10	50	-	-	-	-	Yes	-	Yes	-	Excellent well site work
Canamera	5,43	21	-	21	-	10	-	-	-	-	-	-	Yes	-	Yes	-	Five holes have water sand
G.C.O.S.	86	500	200	-	300	500	-	-	Yes*	-	Yes*	Yes	Yes	-	Yes	Yes	
TOTALS		3,191	1,535	497	1,159	2,437	24	182	285+	10+	10+	10+	14	5	13	7+	
PERCENTAGE OF TOTAL HOLES		100	48	16	36	76	0.75						-	-	-	0.2+	

*See text.

THE INFORMATION GIVEN ON THE TABLE IS THAT SUPPLIED TO THE CONSULTANTS BY THE COMPANIES number of holes without logs. We realize that many, if not all, of these holes have been cored in detail through the oil-bearing section and that they have been designed to meet the company's specific needs in determining reserves. They do not, however, provide adequate information for hydrogeological interpretation and we would certainly recommend that, at least until the absence of hydrogeological problems in a lease has been established, good quality logs be run on a minimum of one hole per section.

Column 7 indicates the number of holes drilled on each lease to the top of the Devonian. Most of these holes have only been drilled to a sufficient depth to identify the position of the top of the Devonian and have not penetrated any significant distance into the Paleozoic formations.

Column 8 indicates the number of holes that have been drilled a significant depth into the Devonian, usually 50 feet or more.

Column 9 indicates the number of water analyses reported.

Column 10 indicates the number of measurements of water resistivity.

Column 12 indicates the number of cases in which water levels were measured and Column 13 indicates the number of pump tests run.

It should be emphasized that columns 9, 10, 11, and 12 cannot be directly related to the number of wells. For example, while a total of 182 water analyses were run, in many cases several water analyses were run on samples from individual wells so that water analyses are not available for 182 wells.

Column 14 indicates whether or not a Devonian top map was available and column 15 whether a basal McMurray water sand isopach map was available. Column 16 indicates whether cross sections across leases were available, without attempting to indicate how much detail was shown on these.

Column 17 indicates whether piezometers or piezometer nests have been installed.

With specific reference to G.C.O.S. Lease No. 86, some resistivity and water level measurements are available for surficial deposits and are mainly of local importance.

Some comments on totals and percentages appear to be in order. An impressive total of 3,191 holes is included. Of these, almost half have high quality logs which is most encouraging for future detailed studies. The number of holes without any logs is approximately 36 percent of the total and is somewhat disappointing but it should be noted that in every case where there are holes with no logs the operator has also drilled a significant number of holes with high quality logs. Assuming that a good distribution of holes with high quality logs is maintained, we cannot strenuously object to some of the holes not being logged unless unusual conditions are encountered.

Approximately 75 percent of the holes have been drilled deep enough to identify the top of the Devonian and hence to determine the thickness of the Lower McMurray water sand where present. This is most encouraging and we trust that this practice will be continued, especially where considerable variation in the thickness of the Lower McMurray or potential water problems in this zone are indicated.

The data shown in column 8 representing the number of holes drilled a significant distance into the Devonian are disappointing, being less than one percent of the holes. We believe that the Devonian section has potential for severe water problems in many parts of the area, although, in many cases, the upper portion may appear quite impermeable. We would certainly urge that, until it has been clearly established that the Devonian presents no problem in a specific area, a considerably larger percentage of the holes be drilled through the Devonian.

Of course, such holes must be carefully abandoned to preclude induced intercommunication between aquifers.

Column 9 reports the number of water analyses at 182. As previously mentioned, in many cases several analyses relate to an individual well so that analyses are available for considerably fewer than 182 wells. The data does not provide enough information to enable us to adequately interpret the water chemistry in the various aquifers.

There have been something over 285 measurements of water resistivity. Although water resistivity can be useful in cases where enough detailed back-up information is available, it does not provide the information on the character of the water which is most important in detailed analysis. For example, between bicarbonate and chloride type waters considerable variations occur, and good analytical data will be essential to determine the source and history of water in the various aquifers. We do not regard resistivity measurements as adequate substitutes for water analyses.

The number of drill stem tests, 10, is very small, as is the number of measured water levels at 10+, and the number of pump tests, also 10+. Several of these may have been run on the same wells so that, at best, there are 30 sources of pressure or related data for over 3,000 wells. This is far from sufficient to provide an adequate comprehension of the groundwater flow systems.

5. GEOLOGICAL SETTING

5.1. Stratigraphy

The general geology of the Athabasca Oil Sands area has been studied and described by many workers. The discussions which follow do not attempt to report on the geology in any detail. Rather, they are intended to provide an introduction to the geologic framework and to emphasize those points which are particularly important to a groundwater study. For more detailed discussions, the reader should refer to detailed geological studies. The most recently published reports are those of Norris on the Paleozoic and of Carrigy on the Mesozoic geology of the region, both published in Carrigy and Kramers (1973). The reports both have good bibliographies which will lead to the earlier work.

The Table of Formations (Table 2) on the following page outlines the pertinent stratigraphic sequence and gives most of the rock unit names in common use. It also summarizes lithology and groundwater characteristics.

The following discussions of rock units are arranged in ascending stratigraphic order.

5.1.1. Precambrian

Precambrian outcrops occur in the northeastern corner of the government-designated Oil Sands area. The rocks are described as metasediments and granite. The Precambrian rocks are considered to form an impermeable basement under the study area.

TABLE 2

TABLE OF FORMATIONS

Age	Group / Formation / Member	Approximate Thickness Feet	Lithology	Hydrogeology
CENOZOIC RECENT		0-30+	Muskeg.	*Very high water content. Serves as recharge blanket.*
			Alluvium.	*Possible source of groundwater.*
PLEISTOCENE		0-200+	Till, sand, gravel, boulders, clay.	*Granular deposits form good groundwater source.*
			- UNCONFORMITY -	
MESOZOIC CRETACEOUS	Grand Rapids	0-300	Sandstone.	*Near-surface bedrock aquifer. Source of springs in Athabasca valley.*
	Clearwater	0-400	Shale.	*Confining beds.*
	Wabiskaw	0-30	Sandstone - glauconitic.	*Clay cemented, low permeability.*
	McMurray	0-350		
	Upper		Sand - very fine, silt.	*(Generally impermeable be-*
	Middle		Sand - medium, crossbedded.	*(cause of bitumen content.* *(Local porous beds.*
	Lower		Sand - coarse, gravel, silt.	*"Lower McMurray aquifer."*
			- UNCONFORMITY -	
PALEOZOIC UPPER DEVONIAN	Woodbend	0-600		
	Grosmont		Dolomite - vuggy.	*Permeable.* *Present only in western part of area.*
	Ireton		Shale.	*Confining bed.* *Present only in western part of area.*
	Cooking Lake		Limestone.	*Permeable.* *Present only in western part of area.*
	Beaverhill Lake			
	Waterways	0-700)	Shale and shaly limestone.	*Generally low permeability.*
	Mildred	140)		
	Moberly	200±)		
	Christina	90±)		
	Calumet	100±)		
	Firebag	170±)		
MIDDLE DEVONIAN	Slave Point	50	Dolomitic limestone.	*Locally contains permeable beds.*
	Watt Mountain	50	Siltstone.	*Generally impermeable.*
	Upper Elk Point			
	Prairie Evaporite	0-800	Salt, gypsum, anhydrite, shale.	*An aquiclude where present. Partly removed by solution.*
	Methy	0-270	Dolomite, in part reefal.	*Locally an important aquifer.*
	Lower Elk Point			
	McLean River	60-160	Shale, silty shale.	*Aquitard.*
	La Loche (Granite Wash)	0-130	Sandstone, arkosic.	*Aquifer of sporadic distribution.*
			- UNCONFORMITY -	
PRECAMBRIAN			Granite - Metasediments.	*Effectively impermeable.*

Aeromagnetic maps published by the Geological Survey of Canada indicate considerable basement structure and topography on the Precambrian surface.

A major, north-northeast - south-southwest trending basement fault has been shown as traversing the study area, crossing the Athabasca River near Township 95. The fault zone affected rocks of Devonian age (Martin & Jamin, 1963). On the basis of present knowledge, the hydrogeological significance of this fault zone can only be surmised but it may well prove to have an effect on the porosity development in Devonian rocks which could result in water communication. Other discussions of faulting are given in the section on structure.

5.1.2. Paleozoic

The Paleozoic section under the area of study is predominantly a carbonate-shale-evaporite sequence. Porosity in a carbonate section is not normally of the intergranular type, but is formed by vugs and fissures, and its distribution is more irregular than that in clastic sediments. Carbonate permeability is dependent on interconnection of vugs and fractures. The treatment of groundwater flow through these rocks should differ from that of flow through sands and gravels for which most groundwater flow and pump test theories were developed.

The Cross Section A-A' (Figure 10), which is from Norris (1973), illustrates the Paleozoic occurrence in the area.

<u>Middle Devonian</u>

i) Lower Elk Point Subgroup

a) <u>La Loche Formation</u>

The La Loche Formation is equivalent to the "Granite Wash". The age of the formation is not certain. In the Oil

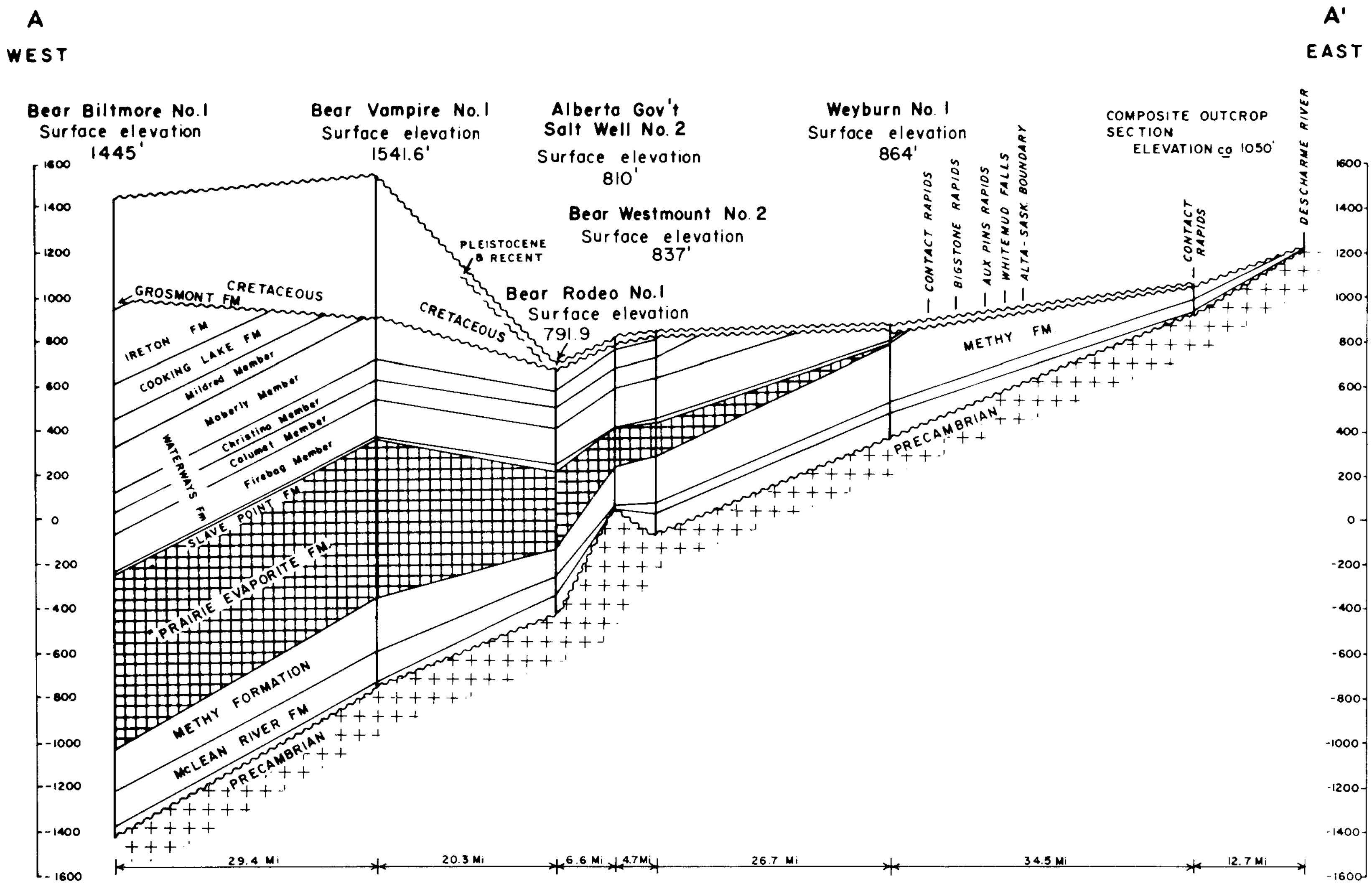


FIG. 10 CROSS SECTION A-A' SHOWING PALEOZOIC SEQUENCE

FROM NORRIS (1973)

Sands area, the La Loche Formation consists mainly of feldspathic and gritty sandstone which varies in thickness from zero to about 130 feet. Variations in thickness are caused by thinning over Precambrian highs and thickening in the lows. It is known to be permeable and to contain salt water in at least one location in the Oil Sands area.

b) <u>McLean River Formation</u>

The McLean River Formation in the subsurface under the study area is predominantly a dolomitic siltstone, with interbeds of silty and sandy shale and mudstone, and thin beds of anhydrite and gypsum. Thickness of the McLean River Formation is known to range between about 60 and 160 feet and, like the underlying La Loche Formation, it thickens and thins in relation to the paleotopography of the Precambrian surface. Hydrogeologically, the formation should act as a caprock or confining bed for any groundwater present in the underlying La Loche.

ii) Upper Elk Point Subgroup

a) <u>Methy Formation</u>

The Methy Formation in the Oil Sands area is composed mainly of dolomite. It is underlain by the fine clastic beds of the McLean River Formation and overlain by the Prairie Evaporite Formation. The formation exhibits biohermal reefal buildups up to 270 feet thick, which are very porous, very permeable, and usually contain highly saline waters. The reefal facies seems to be more prevalent towards the east, near the edge of the Precambrian Shield.

The Methy Formation and the waters contained therein are exceedingly important to the development of the Athabasca Oil Sands. It poses an ominous threat to Oil Sands mining because of the possible upward flow of highly saline formation water into mine openings and higher porous units. The formation, because of its porosity and permeability, has been considered for subsurface waste disposal of mining effluent but possible connections with higher units will have to be studied in detail before this should be attempted.

b) Prairie Evaporite Formation

The Prairie Evaporite Formation is a sequence of evaporites overlying the Methy Formation dolomites and underlying thin Slave Point Formation limestones. Lithologically, it consists predominantly of halite but significant amounts of anhydrite, gypsum, and silty shale are present.

The formation varies in thickness from zero in the east to nearly 800 feet in the western part of the study area. Neither the original depositional limits nor the present eastern limits of the salt are known. Some published maps show the solution edge to the west of the Athabasca River. Present evidence proves the presence of salt farther to the northeast than indicated on the aforementioned maps and outlying remnants may extend still farther east.

The evaporite sequence is very significant to the regional movement of groundwater as major collapse structures caused by solution of the salt beds have affected the stratigraphy and structure of the overlying beds. Several collapse features have been identified on the Devonian paleotopographic surface and suspicions are that some present-day topographic features can be attributed to recent salt solution and subsequent collapse. Highly saline springs on the Athabasca River and other evidence indicate that salt solution is continuing and further collapse can be anticipated.

c) Watt Mountain Formation

The Watt Mountain Formation is a relatively thin, less than 50 feet, shale bed which marks the top of the Prairie Evaporite Formation in the western part of the area. The formation cannot be correlated with any degree of accuracy towards the east. It appears to be of little hydrogeologic significance.

d) Slave Point Formation

The Slave Point Formation is also a relatively thin rock unit of 50 feet or less, and is composed of limestone to dolomitic limestone. The formation does exhibit some porosity and permeability in the study area.

The underlying Watt Mountain shale and overlying Firebag shale member of the Waterways Formation ensure that the groundwater present in the Slave Point Formation would be mostly confined and under an artesian hydraulic head. Collapse structures could have caused fracturing with subsequent movement of saline Slave Point Formation waters towards the surface.

Upper Devonian

i) Beaverhill Lake Group

a) Waterways Formation

The Waterways Formation has been subdivided into five stratigraphic members (in ascending order, the Firebag, Calumet, Christina, Moberly, and Mildred members). In the absence of fracturing, these five members can be considered as one hydrostratigraphic unit because they generally have very low porosity and permeability values. The Waterways Formation varies in thickness from approximately 700 feet in the west to zero at the formation's subcrop towards the edge of the Canadian Shield. Lithologically, the Waterways Formation is predominantly shale and argillaceous limestone.

The pre-Cretaceous erosional surface was carved into beds of the Waterways Formation over most of the study area. Solution of Devonian salt beds and subsequent collapse have caused subsidence of the Waterways.

b) Woodbend Group

The Woodbend Group is subdivided into the Cooking Lake, Ireton, and Grosmont formations. Their occurrence is confined to the subsurface in the western part of the study area and therefore they are of minimal hydrogeological interest as far as Oil Sands extraction is concerned. However, the three formations may be lithologically suitable, and geographically located far enough downdip from the study area, to warrant investigation for subsurface water disposal. The Grosmont Formation, a reefal unit, outcrops near the Vermilion Chutes on the Peace River, approximately 180 miles northwest of the Oil Sands region.

Upper Devonian - Undifferentiated

The remainder of the Devonian section in northeastern Alberta is considered to be too remote from the study region to warrant comment, other than to suggest that some zones may be suitable for deep well disposal of mining effluents and that, although some minor erosional remnants may occur in the study area, no significant hydrogeological effect is anticipated.

5.1.3. Paleozoic-Mesozoic Unconformity

The Paleozoic-Mesozic unconformity in the Oil Sands area is marked by a major change in lithology from the light coloured Devonian carbonates to the overlying sands and other clastics of the Cretaceous McMurray Formation. The Devonian surface has been subjected to prolonged erosion, in the latter stages of which a well developed drainage pattern was created. Solution of Devonian Elk Point evaporites, probably beginning shortly after deposition and continuing intermittently to the present, has resulted in the collapse of overlying formations and has complicated the drainage pattern on the Devonian with the addition of karst-like features.

This complex surface has had a profound effect on the sedimentation and present structure of the Lower McMurray Formation.

The pre-Cretaceous drainage pattern, the karst-like features, and the manner in which the sediments of the Lower McMurray Formation were deposited are significant in terms of the regional and local hydrogeology.

5.1.4. Mesozic

Lower Cretaceous

i) McMurray Formation

From an economic view point, the McMurray Formation is the most important stratigraphic sequence in the area of study. It is, of course, the major bitumen-bearing unit, and the lower part of the formation is a major aquifer, the nature and content of which will be a major factor in determining the economics of oil recovery.

Carrigy (1973) has subdivided the McMurray Formation on lithological evidence into four informal stratigraphic units as follows:

1. Pre-McMurray (?) beds. This zone is described as the isolated remnants of a once continuous sandstone body lying unconformably below the McMurray Formation proper. Outcrops occurring between the Athabasca and Muskeg rivers east of Fort McKay are described as coarse-grained, quartzose sandstone, cemented by silica and goethite. No mention is made of the bitumen content and it is possible that the outcrops on the two rivers may be acting as a source of groundwater recharge to this stratigraphic interval.

2. The lower unit of the McMurray Formation consists of lenticular beds of conglomerate, sand, shale, and silt, most of which have been deposited in the depressions on the Devonian surface. The basal part of the Lower McMurray is often, but not always, a grey residual clay which may be a weathering product of Devonian or younger beds. Where this clay is present in sufficient unfractured thickness, it may act as an aquitard or aquiclude to either upward or downward flowing groundwaters. The overlying Lower McMurray sediments are most often sands, barren of oil and containing large volumes of groundwater under significant artesian pressure. Outcrops of this sand, which is known by several names (basal water sand, basal aquifer, Lower McMurray water sand, etc.), occur in the McKay and Steepbank river valleys. Extrapolation of regional dip would suggest that this basal water sand should outcrop beneath glacial sediments on Muskeg Mountain in the headwater region of the Muskeg River. It is suggested that the various rivers may be providing recharge to this stratigraphic zone.

The Lower McMurray frequently thickens over lows on the Devonian surface. This thickening is usually associated with a low bitumen content and a high groundwater content.

3. The middle unit of the McMurray Formation is an oil-bearing sand with interbeds of silts, shales, and clays. The sequence often shows excellent current bedding which may be of geotechnical significance in mine openings. The typical Oil Sand sequence includes thin aquifers, which appear to be of limited areal extent.

4. The upper unit of the McMurray is similar in lithology to the middle unit but most often is horizontally bedded.

The type section of the McMurray Formation is located along the east bank of the Athabasca River a few miles north of Fort McMurray. The type section is 237 feet thick. The contact with the overlying Clearwater shales is marked by the presence of glauconite and a general change to a marine environment. The top of the McMurray Formation is difficult to pick in the area where glacial erosion has cut down into the McMurray Formation. Large blocks of Oil Sands have been found "boudinage" in the glacially deposited materials.

ii) Clearwater Formation

The base of the Clearwater Formation is marked by the presence of a glauconitic sandstone bed quite different in character from the underlying oil-impregnated McMurray sands. This lower unit is referred to as the Wabiskaw Member. The dominant lithology of the remainder of the Clearwater Formation is grey shale with many inclusions of gypsum. The formation is thought to be of minimal hydrogeologic significance, although the basal Wabiskaw sandstone is an aquifer in certain areas and the water in it appears to have a chemical signature. The shale section may act as an aquiclude.

iii) Grand Rapids Formation

The contact between the Clearwater and the Grand Rapids formations is gradational. The Grand Rapids is predominantly a salt-and-pepper sandstone. Contact springs issuing from the base of the sandstone are a geomorphological feature of the Athabasca River near Fort McMurray. An investigation of the groundwater geology of these springs, including chemical sampling to establish environmental base-line data, would be in the interest of each leaseholder affected.

The overlying Cretaceous Joli Fou, Pelican, and LaBiche formations, which subcrop under glacial deposits sequentially towards the southwest, are not considered to be of enough hydrogeological importance to be discussed further in this report. Lithologically, they are argillaceous sediments of low permeability.

5.1.4. Pleistocene and Recent

The major glacial features of the Oil Sands area are the broad U-shaped valley of the Athabasca, the meltwater channels scoured into the soft Cretaceous bedrock, and the various deposits left behind from the melting ice sheet.

Bayrock (1971) has mapped and published the surficial geology of the Bitumont N.T.S. 1:250,000 map sheet. A preliminary pre-publication map of the Waterways sheet is available from Alberta Research.

These maps indicate the surface location of a myriad of glacially deposited materials. The features of hydrogeological significance are the pre-glacial Athabasca valley and the location of the meltwater channels. Not enough drilling has been done to identify the type of material deposited in these features. If porous and permeable deposits are present, the channels could be significant sources of good quality groundwater for human consumption or, depending on location, could cause a dewatering and/or plant construction problem.

Bayrock has mapped quite large areas of granular deposits, such as outwash sands and ice contact sediments, which could be significant to the groundwater recharge potential into near-surface channel aquifer systems.

Muskeg mantles most of the surficial deposits in the area. The exceedingly high water content of this organic deposit causes great operational problems and, in the case of some lease blocks, precludes many summer operations. The broad areas of saturated muskeg, depending on their topographic location and relationship to the underlying geology, may provide a surface source of water for recharging the groundwater aquifer systems.

5.2 Structural Geology

The Precambrian basement under the study area slopes in a southwesterly direction at approximately 20 feet per mile.

The overlying Paleozonic rocks form a southwest-dipping monoclinal structure with a north-northwest strike. The general monoclinal structure has superimposed upon it local anticlines, synclines, terraces, and some faulting that may relate to basement features or to later causes.

The most dramatic structural features occur in relation to the basin-and-dome appearance of the Devonian surface. This is the result of superposition of collapse features, due to solution of Elk Point Group salt, on a pre-Cretaceous drainage pattern. The solution of salt probably began shortly after deposition and has continued intermittently until the present. Some solution features are, therefore, pre-Cretaceous and were present before McMurray deposition. Some features are probably of McMurray age and some are post-McMurray.

A correct interpretation of the Devonian surface and an understanding of the geological processes which formed that surface are very important to Oil Sands extraction and development. Suffice it to say at this point that detailed knowledge of the Devonian surface and time of salt solution should provide information as to the distribution of the Lower McMurray Formation water sand (aquifer) and also provide an insight into the probable location of upward flowing, highly saline groundwater from the Devonian formations.

Many of the workers who have studied the geology of the Oil Sands area have interpreted major faults underlying the area. Sproule (1938) identified a northwest-trending fault on the Clearwater River south of Fort McMurray. Kidd (1951) reported on the same fault and agreed with its northwest trend. Carrigy (1959) reported an interpreted fault on a northwest-southeast trend running through the Bitumount Basin. He showed, on a cross section, a vertical fault extending to the Precambrian basement near the Athabasca River at the edge of the Bitumount Basin. Martin and Jamin (1963) speak of numerous faults or fracture systems in the Oil Sands region and single out a major northeast trending fault trending through the Bitumount Basin and which affected the pre-Cretaceous drainage pattern.

At the time the above-mentioned studies were made, there was a tendency to extend individual faults or fault systems over considerable distances.

Christiansen (1967), in his report on salt collapse structures near Saskatoon, discussed a structural system comprising numerous individual fault blocks, each bounded by high-angle step-faults. Some of the evidence in the McMurray area, interpreted by earlier workers as indicating very long fault systems, could, in fact, be the result of salt solution.

The necessary knowledge and interpretations of faulting in the area can only come when more data are available.

6. HYDROGEOLOGICAL INTERPRETATION

This section of the report gives our interpretation of the groundwater systems in the McMurray area based on the presently available data. It includes discussions of some of the possible effects of these systems on oil recovery operations and of the possible environmental effects.

It is emphasized that, because of the paucity of adequate hydrogeological data, some of our interpretations are based on extremely limited evidence. They may be changed, and will certainly be expanded, as more reliable data become available.

It has not, of course, been possible to analyze all the voluminous detailed geological data in the time available, nor would it be desirable to do so in a regional study of this nature. Instead, we have concentrated on the available hydrogeological data and its relationship to the regional geologic framework.

In the discussions, references are made to the 3 hydrogeological cross sections and several explanatory sketches which accompany this report, as well as a contour map of the Devonian surface. References are also made to published material and to certain detailed data, such as drill stem test results, chemical analyses, and pump tests which have not been reproduced for inclusion in the report.

Values obtained from various pump tests in the Oil Sands region are shown on the geological cross section. Some of the tests are of longer duration than others and some had more observation wells than others. Generally speaking, the longer the test the more valid the interpretation of transmissibility, permeability, and safe pumping rate values.

The various aquifer parameters shown on the cross sections and referred to elsewhere are taken from reports provided by the various operators but neither the operators nor their consultants should be regarded as responsible for the interpretations indicated.

Although, considering the size of the area, the number of aquifer tests is very small, they still provide valuable data for the present stage of interpretation.

One of the most important aspects of any analysis of groundwater systems is the relative permeability of the various hydrostratigraphic units. Since we have virtually no measured permeabilities, we have had to infer some comparisons from basic geological knowledge.

So far as is practical, we have organized the presentation on a hydrostratigraphic basis. Because of the communication, or possible communication, between hydrostratigraphic units and the resultant interacting effects, it is not practical to maintain a rigid stratigraphic organization throughout the discussion. For example, discussion of the Methy hydrostratigraphic unit inevitably leads to consideration of the possibility of communication with the Lower McMurray and the results therefrom. This means that there is a certain amount of necessary repetition in the discussions.

Our discussions follow.

6.1 Precambrian

It is expected that the only groundwater present in rocks of Precambrian age is that in fracture networks in these mainly crystalline rocks. Core from a well in Lsd. 13-16-91-84 W4M described the granite as fresh, massive, and showing a vertical fracture.

The extent of fracturing in the Precambrian, its areal continuity, and the implications for regional groundwater flow are not known but it seems reasonable to assume that it will be minimal in regional terms and the Precambrian may be considered to form an effective impermeable basement.

6.2 Paleozoic

The Paleozoic section under the area of study is a predominantly carbonate, shale, and evaporite sequence. Porosity in a carbonate sequence is usually vuggy rather than intergranular. It is essential that the treatment of groundwater flow through these rocks be different from that of flow through granular sediments for which much groundwater flow and pump test theory was developed.

Middle Devonian

i) Lower Elk Point Subgroup

a) La Loche Formation

The La Loche Formation (Granite Wash) consists of erosional arkosic detritus deposited on the Precambrian surface. The Granite Wash is porous, permeable, and oil bearing at several locations in Alberta. The areal distribution of this detrital deposit is associated with the Precambrian paleotopographic surface in that the formation is usually thickest in the lows and thin or absent over highs on the underlying surface. In the McMurray area, the La Loche Formation is known to vary in thickness from zero to 130 feet.

The area of any single, thick, porous and permeable deposit is expected to be relatively small. Most occurrences will be confined by the surrounding sediments but the possibility exists that there could be some continuity with the surface to the northeast near the erosional edge of the Devonian.

A drill stem test at Lsd. 13-16-91-8 W4M, over the interval between 1,540 and 1,565 feet, in the La Loche exhibited a weak blow throughout the 60 minute test and recovered 415 feet of muddy salt water. The water was not chemically analyzed. Two other drill stem tests of the La Loche in Lsd. 9-34-94-14 W4M and Lsd. 7-21-89-11 W4M each recovered five feet of mud, indicating low permeability.

According to Carrigy (1969), the lithologic log of Athabasca Oils Ltd. No. 1 well, located in Township 96, Range 11, W4M, drilled between 1911 and 1912, describes two salt water-bearing beds, the Devonian Methy Formation and a reddish sand lying on the Precambrian surface. In the discussion of this well, Carrigy indicates that salt water flowed to the surface from a total depth of 1,130 feet.

Ells (1926) states that a well in Lsd. 8-2-96-11 W4M encountered salt water flows at 765 feet and at 1,000. The drilling date for this well is given as 1915. The drilling method at that time in history was with cable tools.

A driller's report, in the Alberta Mines and Minerals files, for a well located nine miles north of Fort McKay but in Township 96, Range 10, W4M, gives well completion information as follows:

10" casing set at 90'
8½" casing set at 500'
6¼" casing set at 835'
Total Depth - 1,130'

Salt water flows were recorded at 765 feet and 1,000 feet.

Although some minor discrepancies exist in the reports as to time of drilling and location, it appears likely that the three reports refer to the same well. If that is the case, then it is most likely that the lower water flow came from the La Loche Formation. The water was analyzed and contained

36,188 ppm chloride. Ionic ratios are similar to those for the La Saline spring.

The significance of groundwater in the La Loche Formation depends on the thickness and permeability of overlying sediments. Over most of the study area, the waters in the La Loche are probably confined but, given faulting or removal of overburden by glacial erosion as in the Athabasca River valley and the subsequent stress release within the confining sediments, conduits for upward moving water from the Granite Wash could form.

At locations where the La Loche Formation is determined to be permeable and confined, the zone may be suitable for the limited subsurface disposal of toxic mining effluents but it is unlikely that large volumes could be disposed of because of the anticipated limited extent of such reservoirs.

b) McLean River Formation

The lithology of this formation indicates it probably has low permeability and, unless fractured, would act as a confining bed to waters in the underlying La Loche Formation.

ii) Upper Elk Point Subgroup

a) Methy Formation

The porous and permeable dolomitic Methy Formation aquifer, the salinity of the water it contains, and its hydraulic head distribution in any lease block will be very important in Oil Sands operations. The concern for an understanding of the hydrogeologic properties of this aquifer stems from the fact that the Methy aquifer is confined and under relatively high pressure. There is the possibility that dewatering of the McMurray Formation and/or subsequent mining of the Oil Sands with resultant release of pressure may allow highly saline groundwaters to enter mine openings or to enter near-surface or surface systems.

The Methy Formation is a reefal development which was deposited on the generally impermeable McLean River Formation. The Prairie Evaporite Formation salt, where present, surrounds the reefal deposits and acts as a confining bed. By analogy with other areas, it is expected that in some areas where Elk Point salt is present the Methy porosity will be salt filled.

The drilling control to the Methy Formation in the area of study is very sparse, and only after recognition of the possible problems have operators developed a real interest in the unit. This limited drilling control indicates that the Methy is not everywhere porous and permeable but when it is the results can be quite dramatic. One hole in Lsd. 10-25-95-10 W4M lost circulation at a depth of approximately 640 feet after the drill pipe had dropped in the hole (Cross Section B-B'). Circulation was never regained. Water level after loss of circulation was +886 feet (within 60 feet of the present-day topographic surface). Another hole, one mile distant, encountered an essentially tight Methy section.

Porous and permeable Methy Formation sections have recently been identified on the west side of the Athabasca River.

Old records indicate that wells drilled near the Athabasca River in the early 1900's encountered the Methy aquifer under enough pressure to flow salt water to the surface. Some of these wells are still flowing today.

Cross Section B-B', which provides information on the Methy, is drawn from west to east, approximately at right-angles to the regional strike. The west end of the section is at Richfield Oil 14-3 (Lsd. 14-3-87-18 W4M). In this general area, other information indicates that the Methy water contains approximately 200,000 ppm chloride, which would be close to saturation with respect to sodium chloride.

The next well on the cross section with information pertinent to the Methy Formation is the Chaplin well in Lsd. 10-32-88-15 W4M. The Methy was tested in this well over the interval from 2,609 feet to 2,725 feet. The test was of two hours' duration with a recovery of 75 feet of watery mud. This test would indicate a zone of relatively low permeability. No water analysis is available.

Near the Syncrude test pit, which is depicted by a dashed vertical line on the section, a test of the Methy recovered 35 feet of mud, indicating an impermeable zone.

The La Saline spring is shown on the cross section on the east bank of the Athabasca River. Ionic ratios for the water flowing from the La Saline spring are interpreted as indicating that its salinity is probably due to salt solution.

It is possible the Methy Formation will subcrop beneath beds of the Lower McMurray water sand to the east and possibly on the slopes of Muskeg Mountain. Farther east, the Methy will probably subcrop under the Pleistocene glacial sediments. The region east of the line of cross section may well be a source of groundwater recharge to the Methy Formation. Information on the subcrop of the Methy would be helpful in a detailed hydrogeological analysis of the area.

There is some regional information which indicates that Methy waters in the western part of the area may originate deep within the Devonian and flow eastward but this has not been confirmed.

The Methy may, therefore, contain water from both eastern and western sources. Detailed studies of geology, geochemistry, and pressure information from piezometers completed in the Methy Formation will be required to analyze this complex groundwater flow system.

Figure 11 shows diagrammatically Methy Formation and McMurray Formation hydraulic head values at a location east of the Athabasca River. The two wells are only a short distance apart. The water level for the McMurray Formation is about 70 feet higher than that for the Methy Formation. Dewatering of the McMurray Formation and subsequent opening of a pit for extraction of Oil Sands would reduce McMurray heads below those of the Methy.

If Methy pressures were transmitted into permeable beds below the McMurray, the situation sketched in Figure 12 could develop. In this sketch, the confining layer in the bottom of the pit is "blown through" by the hydrostatic pressure exerted from below.

A more detailed diagrammatic presentation is given in Figure 13. This illustrates the case of an upper aquifer with two confining beds and a pumped well from which water is extracted. There is also a lower confined aquifer which is not being pumped. The piezometric surface of the upper aquifer is drawn down by pumping and the downward pressure on the lower bed is reduced. The stresses set up could cause bowing and ultimate fracturing of the confining bed covering the lower aquifer with a subsequent breakthrough into the upper aquifer. In the diagram, the bowing is highly exaggerated.

Cross Section B-B' shows that the protective overburden thickness over the high pressure biohermal reefal development of the Methy Formation becomes less to the east. This thinning of the Devonian section above the Methy increases the likelihood that uplift pressures from groundwater in the Methy reefs could be strong enough to cause fractures and release saline water into mine openings and hence to the surface.

Although the eastern portion of the Oil Sands area has been emphasized, the possibility of excessive uplift pressures

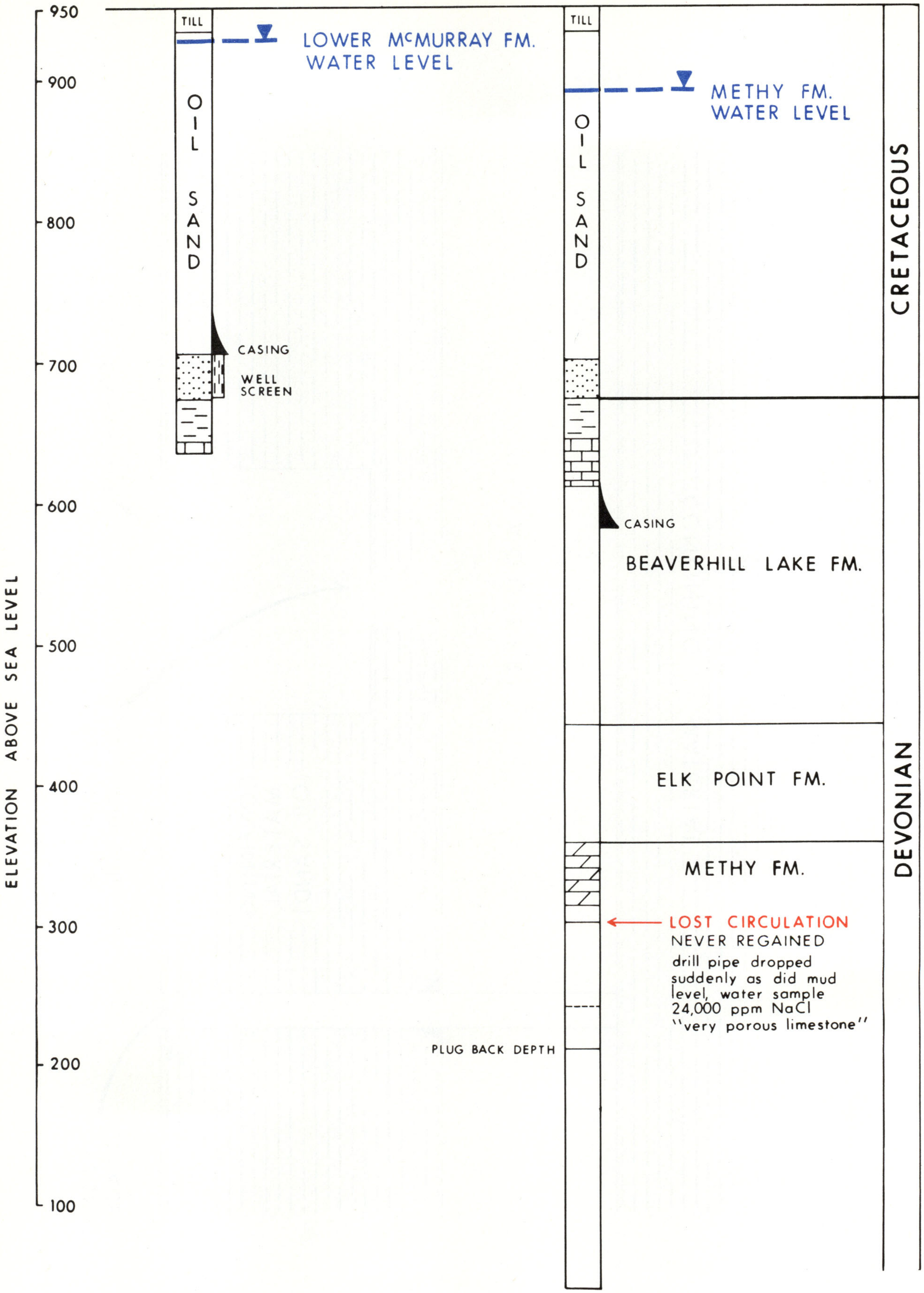


FIG. 11 DIAGRAM TO ILLUSTRATE DOCUMENTED WATER LEVEL DATA FROM LOWER Mc MURRAY WATER SAND & DEVONIAN METHY FORMATION

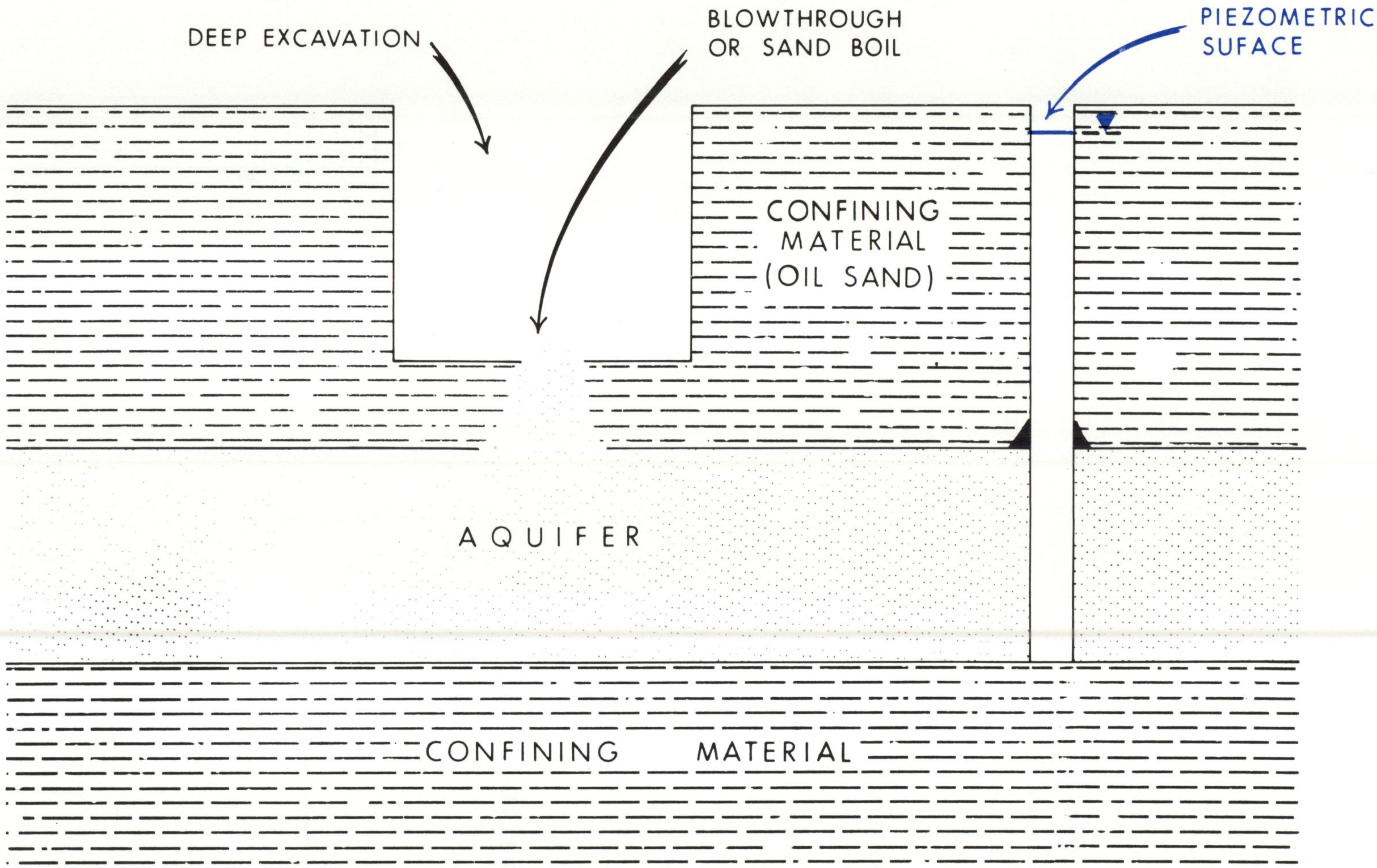


FIG. 12 EXCAVATING IN MATERIAL OVERLYING ARTESIAN AQUIFERS

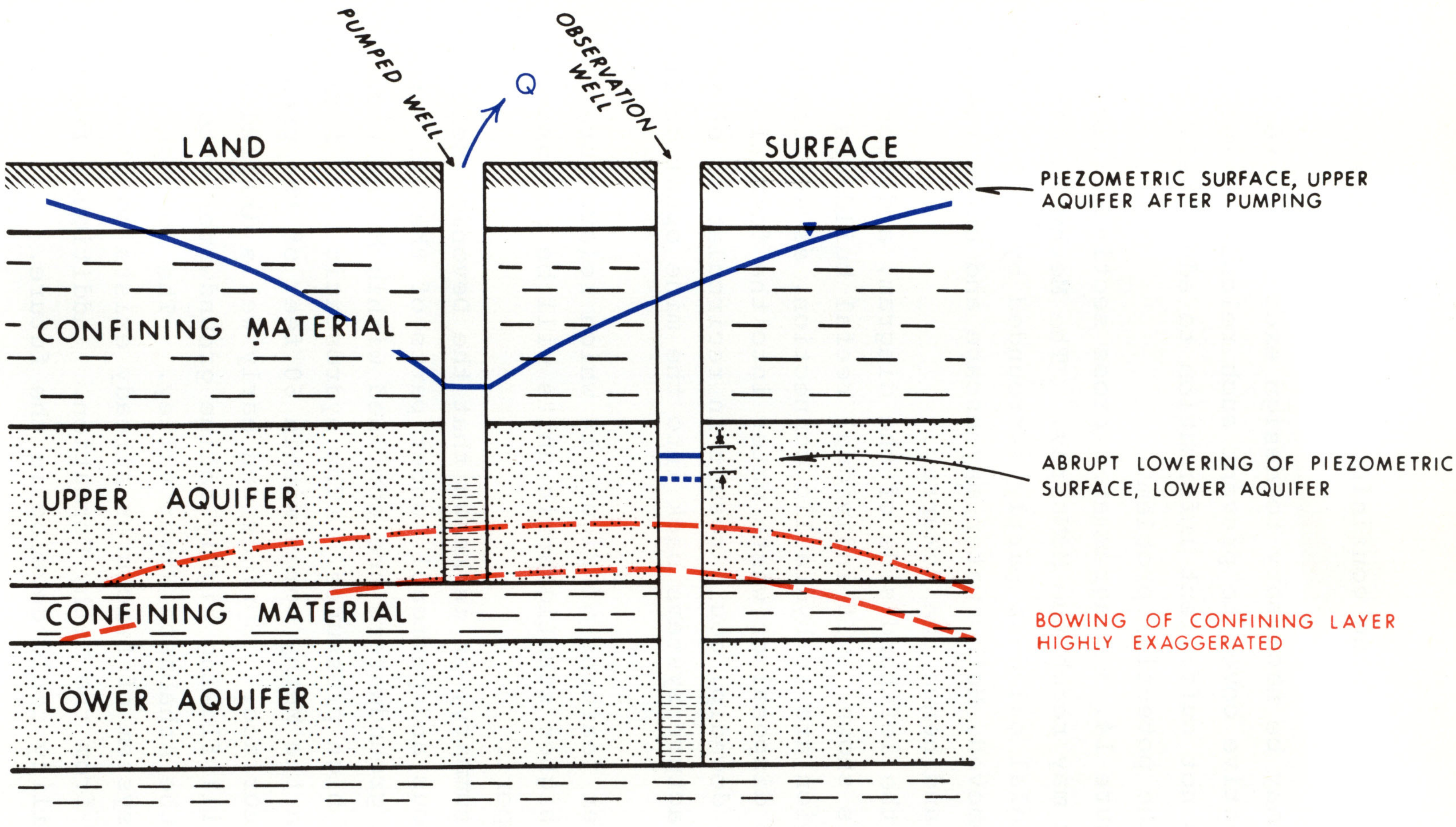


FIG. 13 DIAGRAM SHOWING THE EFFECT ON A DEEP ARTESIAN AQUIFER OF PUMPING FROM AN OVERLYING ARTESIAN AQUIFER

causing failure of overlying confining beds may exist anywhere in the Oil Sands area.

It may be necessary to design excavations to leave sufficient protective cover to prevent such release of water. As yet, there is not sufficient information to adequately define the details of the potential problem.

Figure 14, a diagrammatic cross section, illustrates how Methy waters may reach the McMurray. The Methy Formation is shown as a reefal build-up partly surrounded by salt. Where salt has been removed, Methy water may escape and enter the Upper Devonian, and hence the McMurray.

On the lefthand side of the diagram, a disposal well into the Methy is shown. If individual reefal build-ups within the Methy Formation are in hydraulic connection, as we suspect they may be, the disposal of waste water into the formation, even at some distance downdip, could result in recirculation of the water through fracture systems back into the mine openings from whence it came.

Other features of Figure 14 which relate more particularly to higher stratigraphic units will be discussed later in this report.

In summary, it is known that the Devonian Methy Formation is porous and permeable under parts of the Oil Sands region. Saline groundwaters are confined within Methy reefal structures under high pressures. The hydrostatic head from one well completed in the Methy comes within 60 feet of the present-day topographic surface. Springs and early wells drilled into the Methy are still flowing highly saline groundwater onto the land surface in the Athabasca River valley. The springs indicate that a system of fractures already exists to allow release of water from the Methy Formation. Additional fractures or other permeability could develop in the future.

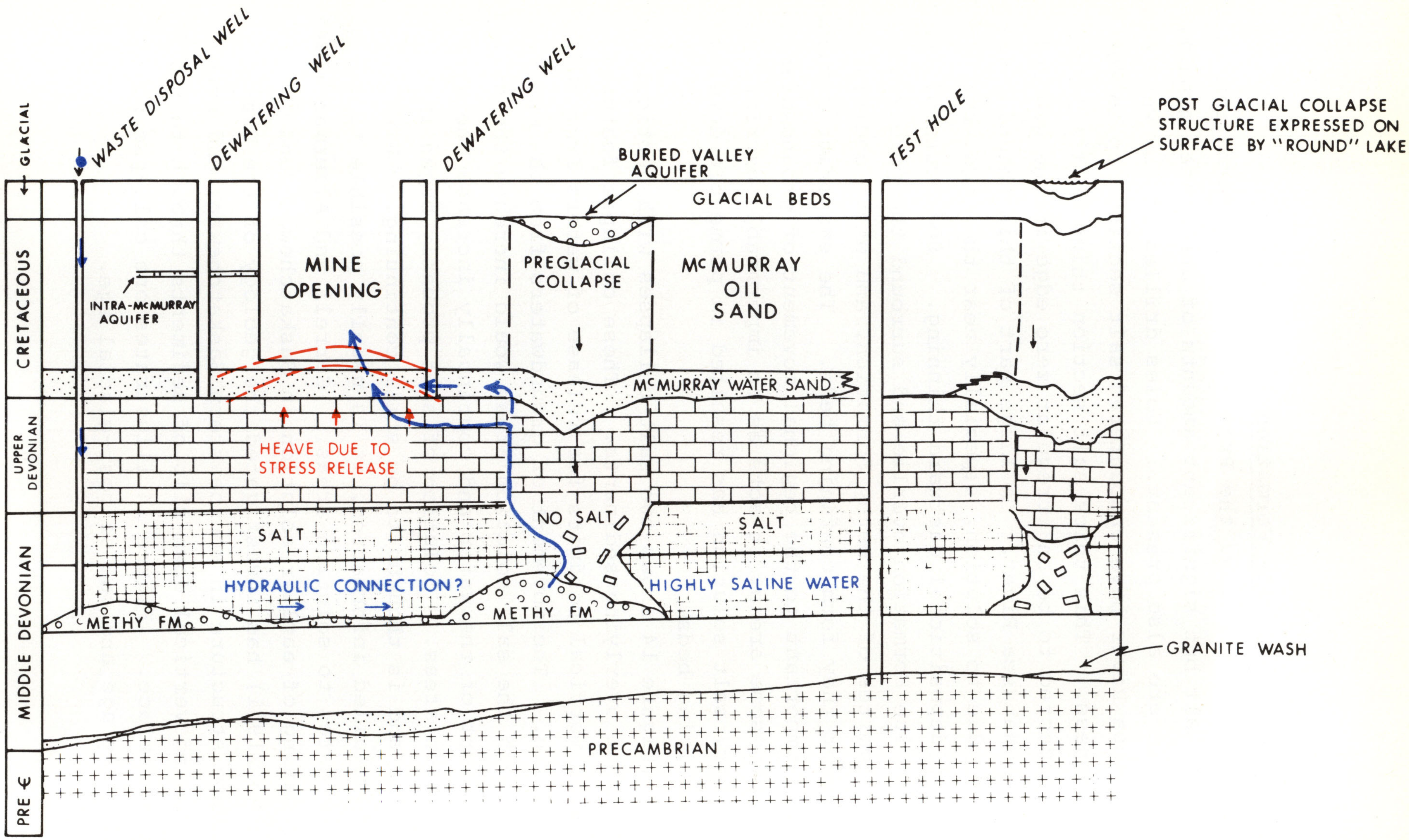


FIG. 14 DIAGRAM TO ILLUSTRATE GROUNDWATER CONDITIONS

McMURRAY AREA

b) Prairie Evaporite Formation

Lithologically, the Prairie Evaporite Formation is predominantly salt but significant amounts of anhydrite, gypsum, and silty shale are also present. Holes drilled on the west side of the Athabasca River have encountered salt sections up to 800 feet in thickness. This thick salt section thins to the east to what is expected to be an irregular zero edge in the general area of the Athabasca River. A large part of this thinning is thought to be due to solution, especially near the edge, but there is also depositional eastward thinning. Sediments of the Prairie Evaporite Formation overlie and surround the porous and permeable dolomites of the Methy Formation, and where undisturbed salt is present they form confining beds. The evaporite sequence is extremely important to the regional movement of groundwater in the area. In some areas, it acts as an impermeable barrier. In other areas, salt solution has resulted in permeable developments in overlying beds.

Figure 14 shows two salt collapses with vertical displacement of overlying sediments. These collapse features would provide vertical conduits for release of waters from the Methy Formation. The movement of groundwaters from the Methy upwards through the salt solution areas would increase the sodium chloride content of the water and continually increase the size of the solution areas. Solution of salt probably began in Devonian time and is thought to be still continuing. With sufficient detailed information, it is usually possible to assign approximate dates to solution areas. Gorrell and Alderman (1968) discussed dating of earlier solution in Saskatchewan, and Christiansen (1971) has investigated the geology of the Crater Lake collapse structure in southeastern Saskatchewan, and noted deformation and vertical down-slip of sediments through to the present-day surface. Figure 14 illustrates one collapse feature of pre-McMurray age and one of post-glacial age.

Drilling through the Prairie Evaporite Formation on the west side of the Athabasca River indicates relatively thick salt sections in most areas. The eastern edge of the salt has been shown in published maps as lying to the west of the Athabasca River. New evidence indicates that salt extends as far east as the Athabasca and remnants may occur some distance to the east of the river. The Devonian erosional surface exhibits a dome-and-basin topography in much of the area. Some of the domes may well be underlain by outliers of Prairie Evaporite salt.

On Cross Section B-B', in a well near the Syncrude test pit, the Prairie Evaporite Formation is shown as being 320 feet thick. The lower 97 feet is predominantly salt. A drill stem test over the interval between 830 feet and 833 feet, which straddled a 15-foot argillaceous dolomite section between the overlying anhydrite and the underlying salt, was a misrun, but 90 feet of water with 9,320 ppm NaCl was recovered. The value of this chemical data is very doubtful.

In summary, the Prairie Evaporite Formation forms the confining beds to groundwaters which are held under high pressure in the underlying Methy Formation. The Prairie Evaporite Formation was subject to solution in past geologic time and evidence indicates that salt solution is continuing. The salt of the Prairie Evaporite Formation thins eastward under the study area. The east side of the Athabasca River has less salt in the Prairie Evaporite section than does the west side of the river. We expect that meteoric waters recharging the Methy have been responsible for much of the solution of the salt in the Prairie Evaporite sequence east of the river. Full knowledge of the effects of salt and salt solution are essential to an adequate hydrogeological study of the area.

c) Watt Mountain Formation

The Watt Mountain Formation overlies the Prairie Evaporite Formation, and is a relatively thin and impermeable shale section that can be correlated in the western part of the study area. The correlation becomes difficult as the Athabasca River valley is approached. The difficulty in correlation of this thin formation may be due partly to its collapse into salt solution areas created in the underlying Prairie Evaporite Formation. The Watt Mountain Formation forms part of the generally impermeable Devonian sequence which, where it is not disturbed, acts as a confining bed or protective overburden thickness to upward movement of groundwater from the Methy and/or Granite Wash.

d) Slave Point Formation

The Slave Point carbonate section is not generally porous or permeable but one of the recently drilled holes on the west side of the Athabasca River encountered a 63-foot section of Slave Point Formation. Log interpretation for this well indicates a six-foot, thin, porous, and water-bearing bed within the Slave Point. It is possible that the Slave Point Formation could locally develop porosity and permeability, and it may contain a significant aquifer under artesian pressures at some locations under the Oil Sands area. Where it is not permeable or disturbed, the Slave Point Formation, like the Watt Mountain Formation, forms part of the protective overburden thickness covering Methy reefal dolomites.

The correlation difficulties noted with regard to the Watt Mountain Formation also apply to the Slave Point in the eastern part of the area.

Upper Devonian

i) Beaverhill Lake Group and Woodbend Group

For purposes of this hydrogeological discussion, the beds of the Beaverhill Lake and Woodbend groups are grouped as one hydrostratigraphic unit. Their lithologic characteristics are similar and they are both generally low in permeability. The total thickness of the two units varies from a maximum of approximately 1,000 feet near the west end of Cross Section B-B' to zero at their erosional edge somewhere on the slopes of Muskeg Mountain near the Precambrian outcrop in the eastern part of the study area.

The hydrogeological importance of these two units is that they form part of the protective overburden thickness that may confine waters of the Methy Formation where salt solution has not affected the permeability of the hydrostratigraphic unit.

The Devonian Surface

A topographic map on the Devonian surface was prepared for the original report. It is not included here. The map was a composite made from maps provided by leaseholders. Some additional control was also used. The Devonian configuration shown on the map was essentially that of the individual lease maps although interpretation was, of course, necessary when connecting contours from lease to lease. Some operators favoured a drainage pattern approach in the contouring whereas others have used a karst topography approach with the presentation of sink holes and topographic highs. Leases showing the drainage pattern approach were generally those in areas where there was not sufficient density of data to warrant a karst approach. We regard the Devonian surface as a karst-like topography imprinted on a stream-sculptured, erosional surface. The karst-like topography has resulted from the solution of the Prairie Evaporite Formation, which commenced prior to McMurray deposition and which is continuing today.

One of the most significant features on the Devonian map was the deep depression in the Devonian surface which straddles the Athabasca River in the northern third of Township 96, Range 11, W4M, near Bitumount, and which is known as the Bitumount Low or Bitumount Basin. Carrigy (1963a) suggests that in very early McMurray time water drained underground into the Bitumount Low. He also states that the drainage channels commonly contain coarse-grained sands and conglomerates.

It is possible that strong features such as the Bitumount Low could not be acting as either subsurface drains for groundwaters in the Lower McMurray Formation or as upward conduits for Devonian waters flowing to the Lower McMurray Formation, and thence probably to the surface as base flow to the Athabasca River.

The Devonian map showed another prominent feature, which is also interpreted as a collapse feature, at the boundary between Townships 94 and 95, Range 9, W4M. Other features with somewhat less relief can be observed throughout the mapped area and undoubtedly others exist but are not defined with the detail now available.

In some areas, there are numerous smaller sink holes which may be difficult to avoid during mining operations and which, in themselves, may present groundwater problems.

The occurrence of thick water sand sections coincident with lows on the Devonian surface is illustrated on the large Cross Section D-D' (Figure 18). In the well in Lsd. 2-29-95-9 W4M, logs suggest that the lower 120 feet of the McMurray Formation is an aquifer. It is not known whether this Devonian low is related to salt solution and subsequent collapse or to erosion on the Devonian surface.

A cross section submitted to the study group, but not presented herein, showed a dramatic thickening of the lower water sand into the Bitumount Basin at Lsd. 16-27-96-11 W4M. Near this well, approximately 240 feet of the Lower McMurray is considered to be water bearing.

The occurrence of Lower McMurray water is not always related to the Devonian surface. Certainly on Cross Section D-D', water sand occurrences are seen to be scattered throughout the McMurray Formation and not necessarily related to lows on the Devonian surface. The first well immediately east of the river, in Lsd. 6-30-95-10 W4M, is located in a low on the Devonian surface and no water sands are present immediately above the Paleozoic sediments. In contrast, the well in Lsd. 7-28-95-10 W4M, located on a Devonian high, is completed with a slotted liner over the lower portion of the hole. It was bailed at 400 barrels per hour and could not be lowered below 160 feet. There is some question as to the source of the water in this well.

Locally, there is evidence to suggest that the weathered surface of the Devonian may form an aquifer.

The well in Lsd. 11-21-95-12 W4M, shown on Cross Section D-D', encountered approximately 20 feet of fractured, cavernous limestone. The excellent well site procedures used at this location permitted the detection of this condition and a water sample was collected. The water contained 11,800 ppm total dissolved solids. Two other wells (in Lsd. 11-13-95-11 W4M), also shown on the cross section, are known to have encountered fractured sections at the Devonian surface.

Where hydraulic continuity exists within the weathered zone, an aquifer of considerable significance may be present.

In summary, a knowledge of the configuration of the Devonian surface will be extremely important in understanding groundwater movements in the Oil Sands region. Individual sink holes may be acting as conduits for upward or downward flowing waters. The pre-Cretaceous drainage pattern carved into the Devonian surface has had a controlling effect on the deposition of the Lower McMurray water-bearing sands. Many low features on the Devonian surface are associated with thick McMurray sand sections. These are interpreted as lows that were present at the time of McMurray deposition. Other low features, apparently of later age, do not show the thickening of the McMurray. Karst-type topography on the surface appears to be most prevalent on the east side of the Athabasca River. Highs on the Devonian surface may be related to salt outliers in the underlying Prairie Evaporite Formation. There is some evidence of the presence of an aquifer in the weathered Devonian surface.

Devonian Thickness

The western part of geological cross section B-B' shows the thickness of Devonian beds between the McMurray Formation and the underlying Methy dolomite as approximately 700 feet. Across the river and to the east, in the well in Lsd. 10-25-95-10 W4M, this protective cover has thinned to approximately 250 feet. From this point, the cover thins rapidly eastward towards the Precambrian outcrops. In addition to the loss of section and therefore protective cover by salt solution, the Devonian erosional surface has been subjected to deep channelling by an ancient drainage network. Thinning of the protective cover has therefore taken place from above and below. Careful analysis of the remaining thickness and the permeability of protective cover between the Methy and the McMurray will be required for each operation.

6.3 Mesozoic

6.3.1. Lower Cretaceous

McMurray Formation

The lithology, thickness, bitumen content, and the general geology of the McMurray Formation have been discussed by many workers. Notable among these is M.A. Carrigy, whose works of 1959, 1963, and 1974 have become standard references on the geology of the McMurray Formation.

Because of the immediate economic interest, there has been a natural tendency to concentrate studies on the bitumen-bearing section of the McMurray. From a hydrological point of view, the water-bearing portions are of more importance.

Some indication of the problems which the McMurray sands may present is given by an old bore hole which was excavated and which flowed water at a rate of 25 gallons per minute with gas. This emphasizes the need for careful cementing of any exploratory wells which could possibly permit mixing of waters.

i) Lower McMurray Aquifer

Most leases have a major aquifer in the Lower McMurray Formation and thinner water-bearing sections may occur anywhere within the McMurray. The Lower McMurray and most of the intra-McMurray aquifers are considered to be effectively confined by the Oil Sands section.

Cross Section B-B' (Figure 16) shows McMurray water levels in Lsd. 10-20-96-7 W4M, at the east end of the section at an elevation of approximately 1,080 feet. The Amerada well in Lsd. 5-26-96-8 W4M is a flowing hole with ground elevation of approximately 1,040 feet. The Fina well in Lsd. 9-9-96-10 W4M has a water level of approximately 890 feet and the Fina well in Lsd. 1-1-96-11 W4M has a water level elevation at about 780 feet above sea level. This progressive drop towards the west in hydraulic head values may well indicate groundwater movement in the Lower McMurray aquifers towards the Athabasca River, but the data are too sparsely distributed to draw a firm conclusion. (The change in direction of the line of Cross Section B-B' from the aforementioned Fina wells to the Shell 10-25-95-10 (W4M) and Home 4-32-94-9 (W4M) wells to the south and east of the Fina holes should be noted.) The progressive lowering of the hydraulic head values towards the Athabasca may also be an indication that the aquifers of the Lower McMurray Formation are recharged on the slopes of Muskeg Mountain and farther to the east.

Pump test results from the Lower McMurray aquifer are shown on Cross Section C-C' (Figure 17) at Lsd. 10-25-95-10 W4M and Lsd. 10-20-96-7 W4M. Transmissibility values of 7,000 gpd/ft and 18,000 gpd/ft were obtained from pump tests of 5,430 minutes and 2,880 minutes respectively. The two Amerada wells (Lsds. 12-19 and 7-28-96-8 W4M) are both flowing holes. The holes were not cased and the origin of the flowing water is in doubt but there are indications that the source was probably the Lower McMurray.

The test in Lsd. 10-20-96-7 W4M, shown at the eastern edge of the cross section, provides an example of a Lower McMurry Formation water sand separated from an overlying water-bearing bed by a thick shale-siltstone zone. The pumping of groundwater did not induce a drawdown in the observation wells completed above the pumped aquifer. This suggests the confined nature of the aquifer and the lack of vertical hydraulic continuity at this location, at least over the time interval concerned.

In some local areas where tests have been run lateral continuity within the Lower McMurray is good. This need not always be the case. The continuity will be strongly affected by the controlling influence of Devonian topography on McMurray sedimentation and the effect of collapse features.

Thick sections of Lower McMurray associated with Devonian erosional lows may be expected to have good lateral continuity. In areas where the Devonian has collapsed due to salt solution there can be vertical continuity with Devonian waters and "bathtub" sinks containing relatively dense saline waters of Devonian origin could be present. The complexities provided by solution effects superimposed on erosional features will be difficult to analyze in detail.

ii) <u>Intra-McMurray Aquifers</u>

The aquifers within the Oil Sands sequence appear to be generally relatively thin and of limited areal extent.

Cross Section D-D' (Figure 18), which runs from the British Petroleum well in Lsd. 11-17-95-12 W4M eastwards across the Athabasca River to the Shell lease, illustrates the difficulty in correlating within the McMurray Formation. Ansley and Beirlmeier (1963) discussed the poor lateral continuity of beds in the McMurray Formation. They attempted, on an experimental basis, to establish correlation based on bitumen content over short distances. Their conclusions were that there is extreme lateral variation and difficult in experience in tracing thin beds, even at 200-foot centres, but thicker beds can often be correlated.

Cross Section D-D' illustrates, at least on the west side of the Athabasca River, the many thin intra-McMurray aquifers. The drilling method employed by British Petroleum on their lease allowed collection of water samples from water zones as they were encountered by the drill. The total dissolved solids content in parts per million of these samples and the estimated flow rates are noted on the cross section at the appropriate depths. Flow rates are generally low. Total dissolved solids content tend to increase with depth to about 12,000 ppm.

The intra-McMurray aquifers may be under pressure. Some test holes in the area have encountered gas flows that have lasted, in one reported case, for two hours, blowing 2-inch diameter rocks 50 feet in the air. Depressurization of such layers will be an important consideration in mine design.

In summary, groundwater in the McMurray Formation occurs mainly in a basal or near-basal stratigraphic position in relatively thick, clean, sand aquifers, generally under considerable artesian pressure. Dewatering of this sand is an engineering problem. The salinity of the water in the aquifer varies from one part of the Oil Sands region to another. It appears that many of the thickest Lower McMurray aquifers are associated with lows on the Devonian surface. Salt solution and subsequent collapse of overlying formations may allow mixing of Devonian and Lower Cretaceous groundwaters.

Figure 15 is a block diagram showing the possible effects of salt solution, and the subsequent collapse of overlying formations, on groundwater systems. The diagram shows waters from the Devonian Methy Formation and the Slave Point Formation migrating vertically through salt collapse areas and mixing with the Lower McMurray aquifer.

Groundwater also occurs in relatively thin intra-McMurray aquifers which are usually of limited areal extent and which can probably be dewatered and depressurized relatively easily. These intra-McMurray aquifers and the four-phase system within the Oil Sands itself may cause geotechnical problems in mining (Hardy and Hemstock, 1969).

Clearwater Formation

The Clearwater Formation in the Oil Sands region is dominantly shale which acts as a low permeability aquitard to water movements.

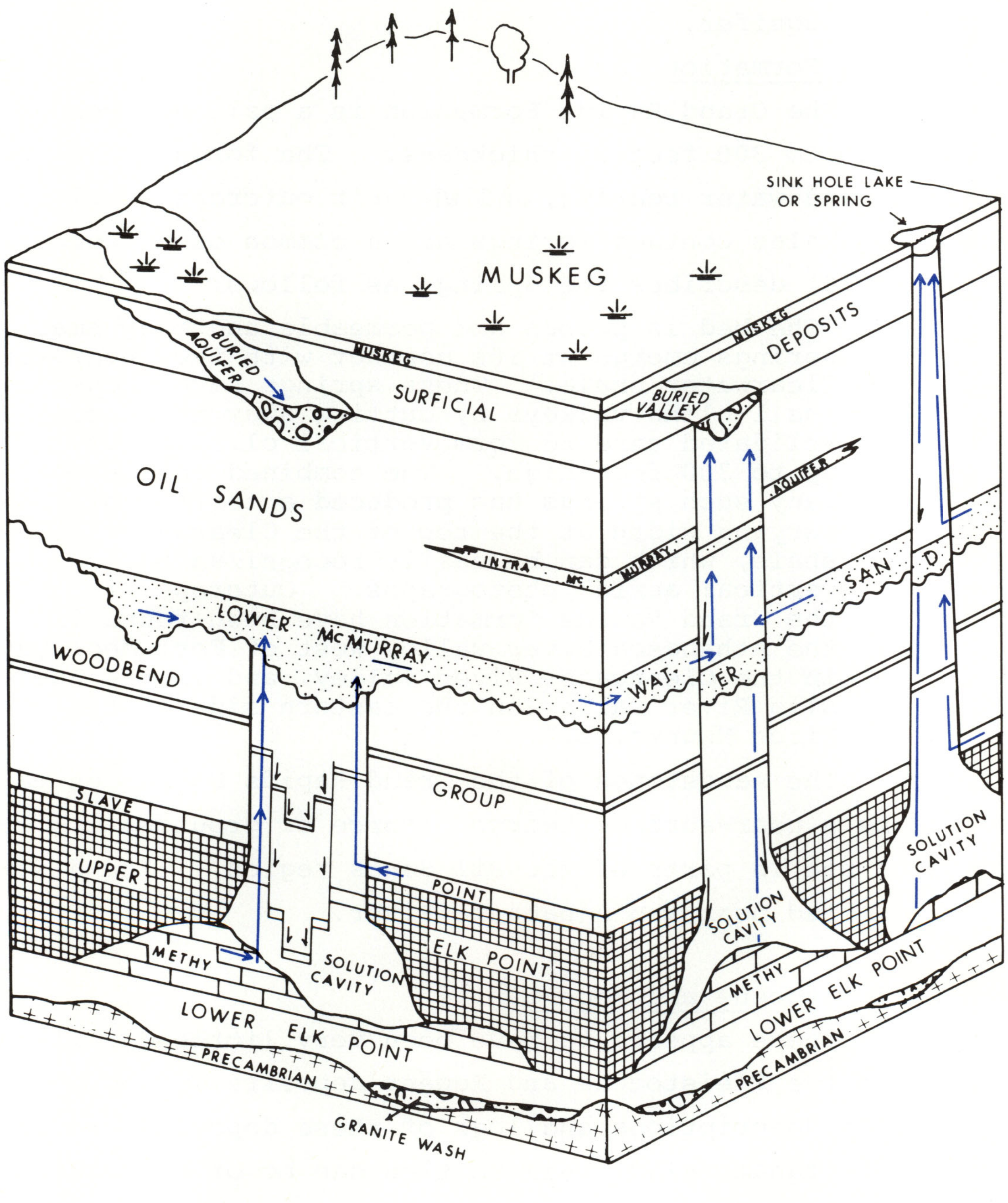


FIG. 15 SKETCH SHOWING POSSIBLE EFFECTS OF SALT SOLUTION ON GROUNDWATER SYSTEMS (not to scale)

The basal 20 feet of the Clearwater Formation (Wabiskaw Member) is most often a fine-grained, glauconitic sandstone bed with silt and clay material infilling much of the porosity. Limited present information indicates that it is not an important aquifer.

Grand Rapids Formation

The Grand Rapids Formation is a salt-and-pepper sandstone up to 300 feet in thickness. The formation is porous, permeable, and water bearing, and where it outcrops overlying the Clearwater shales contact springs are a common occurrence. Carrigy (1973) describes the springs as follows:

> "The bed is porous and permeable and many small springs emerge at its contact with the underlying Clearwater shale. These springs have eroded small blind valleys by cutting away the unconsolidated sand to form vertical cliff faces up to 300 feet high. The combined action of many such springs has produced a terrace of varying width at the top of the Clearwater shale, which can be easily recognized on vertical aerial photographs. Outcrops of the Grand Rapids Formation have been found in the Athabasca River valley west of Fort McMurray, in the Clearwater River valley, and in the upper Ells River valley on the eastern side of the Birch Mountains."

The sandstones of the Grand Rapids Formation may prove to be a near-surface bedrock source of groundwater for industrial use in parts of the Oil Sands region. Its distribution is limited near the Athabasca River.

6.4 Pleistocene and Recent

There appears to have been very little detailed interest in the Pleistocene and Recent deposits in the McMurray area. Good descriptions and logs of these deposits are rare. This is unfortunate since this section can be of considerable importance from a groundwater point of view. The main deposits are till, gravel, sands, boulders, and clay. The sand and gravel beds are often water bearing.

Some of the most important deposits will be those associated with meltwater channels cut into the underlying bedrock surface. Sometimes these channels are floored with saturated coarse sand and gravel. They could provide water supplies for camps and plant operations. The location and areal extent of the meltwater channels in the Oil Sands region are not well known. Few of the many holes in the area provide adequate data for interpretation of the near-surface deposits.

A well in Lsd. 10-24-95-9 W4M pump tested a surficial aquifer at 275 gallons per minute. The interpreted safe pumping rate was 2,000 gallons per minute. This is a very significant aquifer and could cause severe problems in mining. It is strongly suggested that operators in the area make more effort to define the bedrock surface and the nature of the overlying surficial deposits.

We must, once again, refer to the possible effects of salt solution in the area. We have already stated our belief that such salt solution is still active.

Figure 15, a block diagram, shows a buried meltwater valley, the position of which is controlled by salt solution, and the possible infusion of saline waters into the buried aquifer from the underlying Methy Formation.

Figure 15 also shows the possible formation of a sink hole at the present surface due to Recent or future salt solution. Such a sink hole could indicate an area where vertical communication may exist between the surface and the deep Devonian beds. Normally, water movement would be expected to be downward from the surface but deep excavations and removal of pressure could reverse the situation.

Bayrock (1971) has mapped numerous low features, which may be sink holes, in the area of Township 97, Range 10, W4M.

Vertical air photographs of part of the area along Cross Section D-D' show a number of small circular or near-circular lakes. The location of this area of lakes has been marked on the cross section. Other circular lakes are seen in the general area.

Reference has already been made to Christiansen (1971) and his interpretation of the Crater Lake collapse structure in southeastern Saskatchewan. Crater Lake is a circular depression about 800 feet in diameter and 20 feet deep, and appears similar to the lakes seen in the McMurray area. In a companion paper to that of Christiansen, Gendzwill and Hajnal (1971) report on a seismic investigation of the Crater Lake area. They state:

> "Crater Lake is the surface expression of a collapse structure originating from dissolution of the Prairie Evaporite Formation in a limited region. The zone of salt removal is about 800 ft (250 m) in diameter and is closed to the north, south, and east directions. It could possibly open to a channel in a westerly direction. Collapse probably took place by a combination of roof stoping and block faulting, initially in a cavern, then in the chimney about 350 ft (110 m) wide. The structure is probably similar to collapse structures exposed in the Mackinac Straits area of Michigan. Fracturing in the chimney and adjacent rocks has resulted in excess porosity."

Salt solution will collapse of overlying beds is known from other areas and, in some cases, the collapse has occurred catastrophically. Again, quoting from Gendzill and Hajnal (1971):

> "Terzaghi (1970) described subsidence near Windsor, Ontario, due to solution mining of Salina salt from depths of 975 to 1,600 ft (300 to 500 m). An area about 1,000 ft (300 m) in diameter sank about 16 in. (40 cm) over a period of 5 years. This climaxed in 1954 with a catastrophic failure in which a depression about 500 ft (150 m) across and 25 ft (8 m) deep formed within a few hours, destroying much of the surface plant of the mine."

Although the depths and amounts of salt in much of the Oil Sands area are less than those of the Windsor area, it appears that the possibility of future collapse due to solution exists in the McMurray area. The anticipated thicker salt to the west of the river would indicate that the problem could be most severe in this area, but the possibility that outliers of salt exist in the eastern area cannot be discounted. It appears that meteoric waters would have more ready access to the salt in the east and if outliers exist they could readily be dissolved.

The results, although perhaps not catastrophic, could result in significant permeability development and realignment of existing flow systems as well as in significant topographic changes.

Christiansen and Whitaker (1973) have documented the overthrusting of large blocks of bedrock material by glacial action. They have termed this disturbance of the bedrock materials, which has been observed in the Cold Lake area among others, as "glaciodynamic". In parts of Saskatchewan, the glaciodynamic action extends to a depth of at least 390 feet.

It is not yet known whether glaciodynamic thrusting is important in the McMurray area bit it certainly appears possible that it may exist.

Glaciodynamic action on a large scale would certainly have affected the porosity and permeability of bedrock materials and could have an important bearing on groundwater flows and geotechnical problems.

The need for careful study of the glacial beds and upper bedrock section is emphasized.

With training and experience, well site geologists can recognize features characteristic of glaciodynamic disturbance in samples which have been carefully collected under proper drilling conditions.

6.4 Permafrost

Brown (1969) in his "Permafrost in Canada" map shows most of the Oil Sands region to be within the discontinuous permafrost zone and it is highly likely that permafrost exists locally in this region. If present, it may be irregularly distributed in patches ranging in size from a few square feet to several acres. Construction activities can have strong effects on the presence of permafrost, causing it to form or disappear according to the conditions. Stripping of vegetation and muskeg also has strong effects on the occurrence of permafrost.

To our knowledge, there have been no reports on permafrost within the McMurray area, but most of the drilling to date has been conducted within the coldest months of the year and it is quite possible that this is why permafrost has remained undetected.

Geotechnical problems in the Oil Sands are expected to be difficult due to the four-phase system previously mentioned. The addition of another variable in the form of permafrost could compound the problems.

The companies should be aware of the possibility of permafrost and they should attempt to determine whether or not it is present when conditions permit.

7. HYDROCHEMICAL INTERPRETATION

In the preceding section we have made a number of comments on hydrochemistry and certain hydrochemical data have been shown on the cross sections already discussed. Additional discussions and interpretations of available hydrochemical data are presented below.

The chemistry of the McMurray area groundwater systems is important from both the operational and environmental viewpoints. A detailed chemical knowledge will yield valuable information on the origin and history of groundwaters, and will aid in the analysis of groundwater flow systems.

We have stressed in earlier sections of the report the possibility of deep, very saline waters entering the McMurray flow system or other shallower systems. The chemistry of water produced in dewatering systems will be one important factor in designing disposal systems. If there is a connection between Devonian and McMurray aquifers in a specific area, the chemistry of produced water may change with time and production. The chemistry of any water which may enter surface or near-surface systems will certainly be an important environmental consideration.

Presently available chemical control is limited. It tends to be concentrated in a few small areas with many large areas having virtually no control. This distribution of control is indicated in Table 1.

Data available are mostly Oil Sands test drilling. The quality of the data varies. In many cases, because of drilling and sampling procedures, there is ambiguity as to the stratigraphic source of the sample, and there is no doubt that some of the samples represent water from more than one stratigraphic source. In spite of the ambiguities, it has been possible to make reasonable deductions for much of the material. The collection of samples for analysis is discussed in the Recommendations.

Other sources of hydrochemical data include samples from dill stem tests, flowing wells, and springs.

Our present interpretations of the hydrochemistry of the study area are summarized below. For purposes of discussion, three hydrochemical stratigraphic divisions have been used. When more data are available it will be possible to make much more detailed hydrochemical interpretations.

7.1 Devonian Hydrochemistry

Twenty-seven analyses, or partial analyses, of Devonian waters were available for study. The evidence indicates that Devonian waters are predominantly of the sodium chloride type and owe their salt content to solution of evaporitic salts (primarily halite with minor gypsum or anhydrite and some carbonate minerals).

Variations in total dissolved solids content in excess of one order of magnitude occur between the Upper Devonian Beaverhill Lake Group waters and those of the Middle Devonian Elk Point Group. Upper Devonian waters generally have 10,000 to 20,000 ppm dissolved solids and 5,000 to 10,000 ppm chloride. At depth, within the Elk Point Group, chloride concentrations may be over 100,000 ppm and total dissolved solids over 200,000 ppm.

Of the analyses studied, approximately 35 percent showed chloride concentrations over 150,000 ppm. Approximately one-third had chloride concentrations of less than 10,000 ppm, with the remainder containing between 10,000 and 150,000 ppm chloride.

An old chemical analysis of water flowing from a 650-foot deep well at the settlement of Fort McKay indicates a chloride content of over 118,000 ppm. This is believed to be salt solution water. In many respects, the ionic ratios are very similar to those for water recovered more recently from the Methy Formation in Lsd. 10-25-95-10 W5M, although the latter water contained significantly more calcium sulphate.

On the basis of isotope studies, Hitchon (1969) ascribed a meteoric origin to the waters of La Saline spring, located in Lsd. 16-15-93-10 W4M. This spring has in excess of 70,000 ppm dissolved solids, apparently derived mainly from the solution of halite and gypsum.

It has been suggested that west of the Athabasca River, there may be areas where brines from the deeper parts of the Alberta Basin could be approaching the study area. Such waters would likely be rich in calcium and magnesium chloride. There is not yet enough chemical evidence available to determine whether such waters are present in the study area.

On the basis of the observed hydrochemical data, the following processes are suggested with regard to regional groundwater flow in the Devonian aquifers.

1. Devonian aquifers have probably been recharged by infiltration of surface water in the high ground, some distance east of the Athabasca River.
2. Between the eastern recharge area and the Athabasca River, Devonian groundwater probably flows westward, dissolving any remaining salts of the Prairie Evaporite. This has caused, through geoligic time, westerly migration of the eastern edge of the Devonian salt (Carrigy and Kramer, 1974).

Vertical mixing of Devonian and McMurray waters has probably occurred where salt solution has resulted in the development of fracture permeability in the Upper Devonian.

3. In the area generally west of the Athabasca River, the flow is probably not so strong and the direction is not known. In Middle Devonian formations groundwater has approached saturation with respect to halite. Vertical mixing of Devonian water with McMurray waters has also probably occurred in this area. Some older waters from the deeper parts of the Alberta Basin may be present west of the Athabasca but this has not yet been established.

7.2 McMurray Hydrochemistry

There are approximately 100 analyses, or partial analyses, for McMurray waters available in the area. Both sodium bicarbonate and sodium chloride types are present. In the eastern part of the area sodium bicarbonate often forms a large percentage of the total dissolved material. Relatively large concentrations of bicarbonate, in some cases exceeding 3,000 ppm, may also be present to the west of the Athabasca River, but in this area they tend to be masked by the increased chloride content. The bicarbonate content may, in some manner, be associated with the organic content of the McMurray.

Chloride contents range from less than 100 ppm chloride to approximately 15,000 ppm. Twenty-five percent of the samples have less than 100 ppm chloride but over fifty percent have between 1,000 and 10,000 ppm chloride.

In those few areas where there is a concentration of information, it is evident that there is considerable local variation in McMurray salinity. There are also considerable variations in the relative proportions of bicarbonate and chloride in the waters.

In many cases, there is evidence for an increase of salinity with depth. One example shows virtually fresh water at a depth of 100 feet in the McMurray, with progressively increasing total dissolved solids contents of approximately 6,000 ppm at 150 feet, 13,000 ppm at 225 feet, and 15,000 ppm at 300 feet, just below the top of the Devonian. This may well indicate that Devonian waters are migrating upwards into the McMurray.

Although, as previously stated, there is considerable local variation in those areas where sufficient details are available, there certainly appears to be a regional change from fresh to brackish waters in the McMurray on the east side of the river to much more saline waters in this formation on the west side of the river.

7.3 Post-McMurray Hydrochemistry

A total of 68 chemical analyses were reviewed for the post-McMurray deposits.

Water with the Pleistocene deposits are generally of the calcium-magnesium/bicarbonate type, with total dissolved contents of less than 1,000 ppm. However, the chemistry changes quite rapidly with depth to a predominantly sodium bicarbonate type, with total dissolved solids of 1,000 to 3,000 ppm being typical of the Grand Rapids Formation.

Chloride concentrations range from under 10 ppm to approximately 750 ppm and 75 percent of the samples from the post-McMurray deposits have chloride concentrations of less than 50 ppm.

The information which we have obtained gives us no evidence of highly saline waters in the post-McMurray deposits, although about 10 percent of the samples had chloride contents in a range of 250 to 750 ppm.

Except for springs along the Athabasca River, there is no evidence at hand which indicates major flows of strongly saline waters into the post-McMurray deposits. We would not, however, discount the possibility that such flows occur.

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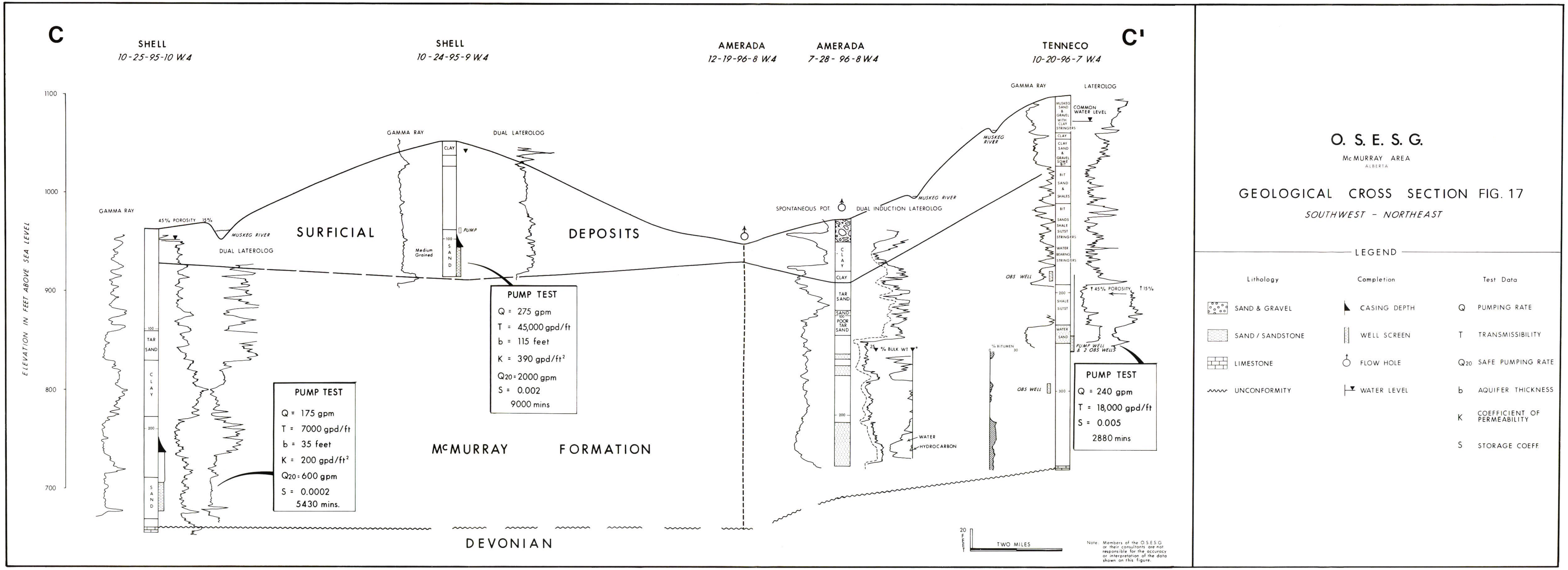
McMURRAY AREA
ALBERTA

GEOLOGICAL CROSS SECTION FIG. 16

SOUTHWEST - NORTHEAST

LEGEND

Lithology	Completion	Test Data	
TILL	CASING DEPTH	Q	PUMP RATE
SANDSTONE/SAND	WELL SCREEN	T	TRANSMISSIBILITY
SHALE	PERFORATIONS	Q_{20}	SAFE PUMPING RATE
LIMESTONE	WATER LEVEL	S	STORAGE COEFFICIENT
DOLOMITE	DRILL STEM TEST INTERVAL	T.D.S.	TOTAL DISSOLVED SOLIDS
ANHYDRITE	SPRING	igpm	IMPERIAL GALLONS/MIN.
SALT	FLOWING HOLE		
UNCONFORMITY			


C
SHELL
10-25-95-10 W.4
SHELL
10-24-95-9 W.4
AMERADA
12-19-96-8 W.4
AMERADA
7-28-96-8 W.4
TENNECO
10-20-96-7 W.4
C'
ELEVATION IN FEET ABOVE SEA LEVEL
1100
1000
900
800
700
GAMMA RAY
DUAL LATEROLOG
45% POROSITY 15%
MUSKEG RIVER
SURFICIAL
DEPOSITS
SPONTANEOUS POT
DUAL INDUCTION LATEROLOG
LATEROLOG
COMMON WATER LEVEL
TAR SAND
CLAY
SAND
Medium Grained
PUMP
PUMP TEST
Q = 275 gpm
T = 45,000 gpd/ft
b = 115 feet
K = 390 gpd/ft²
Q20 = 2000 gpm
S = 0.002
9000 mins
PUMP TEST
Q = 175 gpm
T = 7000 gpd/ft
b = 35 feet
K = 200 gpd/ft²
Q20 = 600 gpm
S = 0.0002
5430 mins.
PUMP TEST
Q = 240 gpm
T = 18,000 gpd/ft
S = 0.005
2880 mins
McMURRAY FORMATION
DEVONIAN
WATER
HYDROCARBON
OBS WELL
PUMP WELL & 2 OBS WELLS
TWO MILES
20 FEET
Note: Members of the O.S.E.S.G. or their consultants are not responsible for the accuracy or interpretation of the data shown on this figure.
O. S. E. S. G.
McMURRAY AREA
ALBERTA
GEOLOGICAL CROSS SECTION FIG. 17
SOUTHWEST - NORTHEAST
LEGEND
Lithology
SAND & GRAVEL
SAND / SANDSTONE
LIMESTONE
UNCONFORMITY
Completion
CASING DEPTH
WELL SCREEN
FLOW HOLE
WATER LEVEL
Test Data
Q PUMPING RATE
T TRANSMISSIBILITY
Q20 SAFE PUMPING RATE
b AQUIFER THICKNESS
K COEFFICIENT OF PERMEABILITY
S STORAGE COEFF

O.S.E.S.G.
McMURRAY AREA
ALBERTA

GEOLOGICAL CROSS SECTION FIG. 18

WEST - EAST

LEGEND

Lithology	Completion	Test Data
MUSKEG	CASING	Q = PUMP RATE
SHALE	WELL SCREEN	T = TRANSMISSIBILITY
SILT / SILTSTONE	SLOTTED CASING	b = AQUIFER THICKNESS
SURFICIAL SAND	AQUIFER ZONE Interpreted from E Log	K = COEFFICIENT OF PERMEABILITY
SAND/SANDSTONE	* ANALYSED WATER SAMPLE	Q_{20} = SAFE PUMPING RATE
CR CLAY REJECT	WATER LEVEL	S = STORAGE COEFFICIENT
MF MILL FEED		igpm = IMPERIAL GALLONS PER MINUTE
OB OVERBURDEN		T.D.S. TOTAL DISSOLVED SOLIDS
BA BASAL AQUIFER		

OCTOBER, 1974

FIGURE 19

Conditions of Use

Gorrell, H.A. (Study Coordinator), 1976. Regional hydrogeological study McMurray oil sands area, Alberta. Syncrude Canada Ltd., Edmonton, Alberta. Environmental Research Monograph 1976-5. 92 pp. plus maps.