HYDROGEOLOGIC EVALUATION OF THE PINE POINT - GREAT SLAVE LAKE REGION

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REPORT TO

NATIONAL HYDROLOGY RESEARCH INSTITUTE
ENVIRONMENT CANADA

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1.0 INTRODUCTION

The purpose of this report is to evaluate the hydrogeologic regime in the Pine Point area and to assess the impact of mine dewatering on the ground water system. The dewatering is for the purpose of open pit mining of the Pb/Zn orebodies located in the limestone barrier reef complex which outcrops in the study area and plunges downdip to the southwest. The barrier reef is a karstified, permeable limestone of the order of 125 metres thick. The hydraulically active portion of the reef has been conceived to include a 10 to 15 kilometer wide area bounded on the north by the Buffalo River shales and on the south by the Muskeg evaporites, both of which are considered to possibly be time-equivalent stratigraphic sequences of the reef. However, the width of the barrier reef is quite variable. Reef facies are in fact mapped on the northwestern shore of Great Slave Lake (GSL). Watt Mountain Shales overlie and confine the reef in the western part of the study area. The barrier reef is underlain by the Keg River dolomite which is considered to be a relatively permeable unit throughout the area, although substantially less permeable than the overlying barrier reef complex. Below the Keg River formation lies the Chinchaga evaporites. Considering the geologic and structural complexity and subtleties in the area, the foregoing may seem an oversimplification, however, it is considered a useful and instructive starting basis on which to develop a quantitative assessment of the effects of mine dewatering.

The depth, lateral extent and nature of karstification in the south GSL area is the subject of renewed interest in the past several years. The nature and extent of the karstification is of considerable interest and importance to an evaluation of the impact of mine dewatering on the ground water system. Unfortunately, there are no piezometric, permeability or other direct measurements on which to firmly establish the extent of the interformational hydraulic interconnection which might be provided by deep seated karstification or solution channeling. Therefore, without direct measurements to the contrary and considering the permeability contrasts of the reef complex and the geologic units immediately surrounding the reef, the Chinchaga evaporites are considered to be a relatively low permeability lower boundary to the active ground water flow system in the area. However, flexibility has been retained in the 3-Dimensional ground water flow model of the area by including the Chinchaga Formation within the modeled flow region. Should evidence be obtained of higher permeability at depth and should there be some indication that dewatering may have some influence on the ground water system below the Keg River Formation, it is possible to vary the permeability of the lowermost unit correspondingly.

A quantitative assessment of the effect of mine dewatering on the hydrogeologic system is attempted in this report by employing a numerical 3-Dimensional ground water flow model. The geometry of the geologic system and the permeability configuration suggested by this geometry implies that pumping test analysis using analytical solutions to the ground water flow equation may be inadequate to determine the overall effect on the 3-Dimensional flow system; however, for mine operational purposes, standard pump test analysis has been reasonably successful in developing the dewatering program at the mine over the past 15 years. Recent dewatering operations have apparently deviated somewhat from predicted conditions (Durston, 1979) and a ground water flow model, which allows spatial variations of hydraulic parameters, is considered a reasonably useful tool for quantitative data assimilation and predictions.

The 3-Dimensional flow model is used in this study for the purpose of quantitatively assimilating the existing hydrogeologic conceptualization of the area and assessing the impact of the mine dewatering based on this "first cut" assimilation. The modeling results are intended to indicate the possible extent of influence of the dewatering operations, and to assist in developing the data needs which would assist in the evaluation of dewatering effects at distance or depth. The modeling study does not proceed through a sensitivity analysis, but rather shows the extent of influence which would occur if the hydrogeologic conceptualization, the hydrostratigraphic configuration and hydrogeologic boundary conditions presented in this report are representative. Sensitivity analysis and "fine tuning" in the immediate mine area where the data are more numerous are beyond the scope of this study.

2.0 GENERAL GEOLOGIC SETTING

This section discusses the geologic history and development of the stratigraphy in the Pine Point area for the purpose of providing sufficient information for the reader to independently evaluate the representativeness of the following hydrogeologic conceptualization of the area. The section does not attempt to provide a detailed interpretation, but rather presents the geologic system as assessed and interpreted by the experts on the area. Although some differences of opinion exist on the reef facies development, nomenclature, and of course ore genesis, overall depositional environment and geologic history appear reasonably consistent.

The Pine Point area is situated near the surface interface of the Western Canada Sedimentary Basin (WCSB) and the Canadian Shield, at the northeast limit of the Western Canada Interior Platform. The Interior Platform is part of the stable interior region of the continent referred to as the North American craton. Generally, the formations present consist of sedimentary rocks ranging in age from Proterozoic to Recent, overlying a west-dipping surface of Precambrian igneous and metamorphic rocks (Meijer-Drees and Davies, 1976). The sedimentary sequence is relatively undisturbed dipping gently towards the southwest, with most formations or lateral equivalents extending at depth into northeastern British Columbia. At the western limit of the Interior Platform the succession is folded and faulted to form the Cordilleran Orogen.

The ore host formations at Pine Point comprise part of a broad barrier reef carbonate buildup referred to as the Presqu'ile Barrier Reef (Figure 1) which extends from near the Canadian Shield in the northeast to the interior of British Columbia in the southwest. The Pine Point area was a significant geologic control area during creation of sedimentary formations in middle Devonian times. During this period, the barrier reef separated the Elk Point Evaporite Basin on the southeast from the Mackenzie Shale Basin on the northwest (Figure 1). The overall width of the barrier is quite variable extending as far as the north shore of GSL at some points (GSC, 1974). A regional tilting of the entire basin has produced a regional dip of approximately 4 m/km (Rhodes, 1981).

Two major fault zones, referred to as the McDonald and Preble Faults, are present along the south shore of Great Slave Lake and are oriented northeast to southwest (see Appendix 1; GSC, 1974). The McDonald fault zone at N45°E can be traced for over 500 km in Precambrian rocks of the Canadian Shield to the east of Pine Point with coverage by sedimentary strata occurring just east of Pine Point (Kyle, 1981). This fault has also been identified along its projection in the subsurface formations in northeast British Columbia. Kyle (1981) noted that "this trend marks a major zone of prolonged tectonic disturbance which first became active in early Proterozoic time". The influence of these deep-seated structures on the overlying sedimentary sequences is uncertain.

2.1 Stratigraphy

The regional stratigraphy in the area surrounding the Pine Point mining district generally consists of a sedimentary sequence of west-to southwest-dipping limestones, gypsum, dolomite and shale. The succession to the south of the Pine Point ore bodies, in ascending order comprises: the Old Fort Island, Mirage Point, Chinchaga, Keg River (or Little Buffalo River), Nyarling (or Muskeg), Watt Mountain, Slave Point, and Hay River Formations (Figure 2). In the Pine Point mine area the stratigraphy becomes much more complex due to the presence of the Pine Point or Presqu'ile Barrier Complex, which lies between the Keg River and Watt Mountain Formations. The Barrier Complex consists of the Sulphur Point, Presqu'ile and the Pine Point Formation. To the north of the barrier reef, the Buffalo River Shale occupies roughly the same stratigraphic position as the Pine Point Group; that is, between the Keg River and Watt Mountain Formations. The Muskeg evaporites occupy the equivalent stratigraphic position to the south. A brief discussion of the individual stratigraphic units has been adopted from a number of sources including Norris (1965), Skall (1975), Skall (1977), Kyle (1981), and Rhodes (1981).

The Old Fort Island Formation is considered to overlie the granitic Precambrian at all locations except at topographic highs on the irregular Precambrian surface. Little is known of the Precambrian/Ordovician contact in this area although a rough downward slope of 24 feet per mile at an azimuth of 240° was identified by Norris (1965). The sandstone of the Old Fort Island Formation was described by Norris (1965) to consist of "thin- to thick-bedded, fine- to coarse-grained, varicoloured but mainly white, friable, quartzose sandstone; some thin beds of greenish grey and dusky red siltstone; and occasional laminae and partings of green shale".

The Ordovician Mirage Point Formation overlies the Old Fort Island Formation in most locations and the Precambrian in others. The formation is comprised of a thinly bedded sequence of argillaceous, sandy, gypsiferous dolostone as well as dolomite mudstone, very fine-grained dolomitic sandstone and shale and gypsum. Mud cracks and irregular veinlets of gypsum have been noted (Norris, 1965). Ordovician and/or older Paleozoic formations reach a maximum thickness of approximately 300 metres in the northwestern part of the GSL region. The Mirage Point Formation underlies the entire study area, subcropping to the east of Pine Point on the east side of the Slave River.

The Chinchaga Formation of Middle Devonian age unconformably overlies the Mirage Point Formation. The Chinchaga Formation is present throughout most of the area, subcropping along and to the west of the Slave River (GSC, 1974). The unit consists of light grey to brown anhydrite with minor amounts of brown to brownish-grey, dense, fine crystalline dolomite. Some brecciated limestone and dolostone and contorted and brecciated anhydrite are also present (Kyle, 1981). The Chinchaga is considered by Norris (1965) to be a relatively tabular unit in the area under study.

The Keg River Formation, or Little Buffalo River Formation, of early Givetian age, conformably overlies the Chinchaga Formation. The unit consists of medium to dark grey-brown, dense to sucrosic dolostone with varying amounts of argillaceous and carbonaceous material and chert nodules (Kyle, 1981). Some micritic limestones and calcareous shales are present. The presence of this Formation throughout the Pine Point barrier reef was maintained during faulting, although tectonic adjustments resulted in a greater formation thickness to the south of the reef than to the north. This formation outcrops as an escarpment along the Little Buffalo River from just south of the Alberta border to the Nyarling River. The outcrop is referred to as the Little Buffalo River Escarpment.

The stratigraphy of the Pine Point barrier reef is complex (Figure 3), consisting of several formations and many more lithofacies. These are well described by Skall (1975, 1977). A short discussion is provided in the following section.

The Pine Point barrier is comprised of the Pine Point, Presqu'ile and Sulphur Point Formations. The Pine Point Formation is the oldest in the group. A thick overlying dolomite is differentiated by Norris (1965) but is included in the Pine Point Formation by Skall (1975). Several facies have been identified by Norris (1965) within the Pine Point Formation which included limestone, dolomite and shale units (Figure 3). Maximum bedding attitudes were identified by Norris (1965) at 8° near Dawson Landing, northeast of the Pine Point town site.

The Presqu'ile Formation, overlying the Pine Point, is described as a "light-coloured, coarsely recrystallized, variably vuggy, massive dolomite" by Belyea and Norris (1962). It is overlain at some locations by the Sulphur Point Formation and at most points by the Slave Point Formation. The coarsely recrystallized dolomite, at some locations, grades into and interfingers with the undolomitized reefal and associated limestone facies which are excluded from the Presqu'ile Formation and comprise the Sulphur Point Formation (Figure 3). Dips in the Presqu'ile have been identified at 1° to 2° to the south/southeast (Norris, 1965). The equivalent of the Presqu'ile Formation which Skall (1975) denoted as facies K (Figure 3, Table 1) is noted to have a maximum thickness of 65 m along the Main Hinge and 20 m along the North Hinge (Figure 4) although a large variation in thickness occurs. The distribution of the Presqu'ile is restricted to the area between the Hinge Zones and below the Post-Middle Givetian Watt Mountain Formation (Figure 4).

The Sulphur Point Formation is the equivalent of the undolomitized Presqu'ile Formation. The Sulphur Point consists of a variety of relatively fine-grained limestones interfacing with the Presqu'ile Formation and forming an indistinct boundary at the Formations' interface. The Sulphur Point covers a large area and may be traced into northeastern British Columbia. To the northwest of the barrier, the Sulphur Point grades into the Buffalo River shale. To the southeast, the Sulphur Point Formation interfaces with the Muskeg Formation along the irregular southern boundary of the barrier reef.

The Muskeg or Nyarling Formation is described by Kyle (1981) as white to light brown bedded anhydrite which may be nodular, mosaic laminated or massive and is also noted to contain dolomite (Belyea and Norris, 1962). Exposed areas viewed by Norris (1965) consisted mainly of gypsum with minor amounts of limestone. This Formation reaches its northerly limit along the south edge of the Pine Point mining area upon interfacing with the Pine Point Group. The Muskeg Formation can be traced into northern Alberta and Saskatchewan where it grades into the extensive salt formations of the Elk Point Basin and can also be traced into northeastern British Columbia (Figure 1). The belt is poorly exposed with few outcrops. Its subcrop region is characterized by relatively flat terrain with large areas of muskeg and sinkholes (Norris, 1965). A maximum thickness of 39 metres was calculated by Norris (1965) using an assumed dip of 2.5 metres per kilometre.

The Buffalo River Formation, a unit of green shale in excess of approximately 50 metres thick, forms the stratigraphic equivalent of the Presqu'ile and Upper Pine Point Formations to the north/northwest of the barrier. The Buffalo River Formation pinches out to the south near the reef and its northern limit is not known. This formation is considered as part of the Pine Point Formation by Norris (1965).

The Buffalo River Formation and overlying B Biostromal Formations are now recognized as Formations by Pine Point mine geologists (Rhodes, 1981). These Formations are considered to be younger than the Pine Point Formation and to not interfinger with but overlie the Pine Point and Sulphur Point Formations.

The Watt Mountain Formation overlies the reef complex and the Buffalo River and Sulphur Point Formations. The lower Watt Mountain Formation according to Rhodes (1981) "is composed of light cream to grey micritic limestones with several blue green shale beds; the Upper Watt Mountain Formation tends to be micritic limestones or fine grained dolomites... ". The Watt Mountain Formation varies in thickness between 8 and 16 metres over the barrier complex, however it thickens considerably away from the reef complex. The distribution of the Watt Mountain is apparently discontinuous on the regional scale as Norris (1965) found it was not identifiable in all wells in the region.

The Slave Point Formation which subcrops to the west of the Pine Point area, overlies the Watt Mountain Formation. Four facies are described by Kyle (1981) which consist of mostly limestone with dolomite mudstone and the AMCO shale member at the base. Outcrops are noted along the south shore of GSL and in the lower reaches of the Buffalo River. Outcrops are noted as far south as the Alberta border and in numerous sinkholes between the Alberta border and GSL as is evident in Appendix II. The Hay River Formation consists of a sequence of Upper Devonian limestones and is often included as the uppermost unit of the Slave Point Formation. A generalized geologic map and cross-section are given in Figures 7 and 8, respectively.

Regionally the Pine Point area has a Pleistocene surficial deposit cover consisting principally of ground and hummocky moraine (Bayrock, 1976) which is covered in many areas by glaciolacustrine clays. The surficial deposits along the south shore of GSL consist of glacial till, lacustrine and beach material. Glacial till deposited by the Laurentide ice sheet consists, at the near surface of gravelly sandy loam to stony gravelly sandy clay loam (B.C. Research, 1977). The near surface till is often reworked by wave action of the glacial lakes. At lower topographic elevations, clay to silty clay lacustrine deposits predominate. Beach deposits, which developed in ridges sub-parallel to the Pine Point ridge, cover a large area. The texture of the beach ridges is variable, but usually consists of sandy material.

Beach ridges are underlain by till or lacustrine deposits, with the till usually present at depth at all locations. Some interbedded sand and clay deposits are encountered in the till as well as occasional layers of cemented sand particles forming what is referred to as hardpan. The area is denoted as a zone of intermittent permafrost on a regional scale although Durston (1979) noted that permafrost is seldom encountered in the immediate Pine Point area. Overburden depths generally range from 3 to 45 metres and were noted to average about 15 metres near the ore bodies (Durston, 1979).

2.2 Structural Geology

Upon analysis of the geological information available at Pine Point Mines, Campbell (1950, 1957), as referenced in Norris (1965), identified "numerous closely spaced gentle flexures in the form of anticlines, synclines, domes, and basins as well as minor faults, all trending more or less between 240T (240°) to 245T (245°). The average plunge of the folds is 22.6 feet per mile to the southwest". Minor folding is associated with differential compaction, gentle flexing and differences in rates of subsidence in the original sediments. The Precambrian faults (MacDonald and Preble) identified on GSC (1974) (see Appendix I) are oriented at approximately 225° according to Norris (1965) who suggests that these features are tectonically unrelated. However, Vogwill (1976) attributed faulting and fracturing in the Devonian to tectonic movements in the basement Precambrian and identifies two fault orientations, namely northeast to southwest and east to west. Normal faults identified in the middle Devonian strata along the Buffalo River have displacements of 36.5 metres and 9 metres at 13 and 5 kilometres south of the river mouth, respectively, with the northwest side of the fault rising above the southeast side (American Metal Company as referenced in Norris, 1965). Both faults are shown on the GSC (1974) map with the fault at the 13 kilometre mark shown to extend northeasterly from just west of the Buffalo River through the Pine Point mining area to Dawson Landing on GSL.

On a local scale, faulting was noted in pit A-55 (Figure 5) and took the form of a sequence of low-displacement normal faults without any one fault exceeding a displacement of 1 metre (Alldrick, 1982 as referenced in Weyer, 1982). Normal faults with 1.5 to 9 metres displacement were observed at a number of locations on Pine Point property (Rhodes, 1981).

2.3 Development of Pine Point Area Geology

The development of the Pine Point mine area geology is summarized below based on Skall (1975) which should be referenced for a more detailed discussion. Skall (1975) found that previous subdivisions of the stratigraphy at Pine Point were inadequate to describe the geology and developed a further breakdown shown in Figure 3 and Table 1. It should be noted that the intention of this section is simply to present a representation of the local geology of the Pine Point area in sufficient detail to facilitate an interpretation of the hydrogeology. The geology of the Pine Point barrier reef is comprised of complex lateral and vertical variations of which a description is beyond the scope of this report and is described elsewhere (Skall, 1975; Skall, 1977; Kyle, 1981; Rhodes, 1981).

The formation of the barrier reef was initialized in early to middle Givetian time by a gentle arching of the Keg River Formation along the MacDonald or East Arm Fault. The Keg River Formation is denoted as Facies A in Figure 3. Further description of individual facies is provided in Table 1.

The initial carbonate shoal developed into a barrier reef complex with accompanying South Flank Back-reef Facies (J), Fore-reef Facies (E) and the Basinal Tentaculites Facies (F) as denoted by Skall (1975) (Figure 3; Table 1). The barrier continued to develop, isolating extensive evaporative pans to the south in which evaporites (Muskeg Formation) were precipitated; from the open sea to the north where a series of shales (Buffalo River Shale) were deposited. The Muskeg Formation and the Buffalo River Shale (denoted G) are shown in Figure 3 and described in Table 1.

Tectonic adjustments along what is referred to as the South Hinge (Figure 4) resulted in an accelerated rate of subsidence to the south of the barrier. Precipitation of evaporites continued in the south with up to 400 feet of interbedded evaporite and dolostone forming the Muskeg Formation (Skall, 1975) (Figure 3). Although a greater rate of subsidence continued to the south, the north side of the barrier continued developing towards the open sea, keeping pace with a more limited rate of subsidence than in the south.

The presence of the evaporite pans to the south is considered to be related to the dolomitization of the lower part of the barrier through reaction of limestones with percolating magnesium-rich evaporative sea waters. Fine dense to sandy dolostones were formed and now compose the major portion of the Pine Point Formation.

A second tectonic disturbance marked a distinct change in sedimentary rock formation and resulted in the creation of the Main and North Hinge zones (Figure 4). Skall (1975) suggests that this disturbance began at a late stage in barrier reef evolution and continued into the late/middle Givetian period, prior to depositon of the Watt Mountain Formation. An even greater rate of subsidence in the south occurred at this time than had previously been experienced and a much larger area was flooded. The subsidence of the area south of the barrier, although greater than previously experienced, occurred over a shorter period of time. Sea water influxes were not sustained over a long period resulting in little dolomitization in the upper part by the same process as the dolomitization in the lower part of the barrier. Continued development of the Organic Barrier Reef Facies (D) and Shallow Fore-reef Facies (C) occurred along with the Back-reef Facies (H and I) (Figure 3, Table 1).

Marine regression resulted in cessation of the development of the Pine Point barrier reef complex, but some deposition continued in lower-lying areas. A partial disconformity and karst surface development occurred in the upper topographic portions of the barrier for which evidence suggests that the barrier was a minimum of 30 metres above the sea level present at that time (Skall, 1975).

Dolomitization of some portions of the upper part of the reef, to form what is known as the Presqu'ile Formation, has been linked by Skall (1975) to an influx of magnesium-rich ground waters along the North and Main Hinge areas. The formation of this distinct course-grained dolomite may have been related to ground water flow through the extensive network provided by fractures and karst features.

Late Givetian deposition is attributed to a more or less uniform rate of subsidence over the entire area between northern Alberta and Great Slave Lake. The Watt Mountain Formation directly underlying the Slave Point Formation was formed through deposition by tidal flat sea waters. The Slave Point Formation was also formed from tidal water deposition but was subject to steadily increasing subsidence rates.

As hinging was instrumental in the development of the geology at Pine Point, the facies interfaces are closely tied to the hinge strike of N65°E. The termination of the evaporite front or Muskeg Formation occurs at the South Hinge, and the North Hinge closely parallels the southern limit of the Buffalo River Shale (Figure 4) (Skall, 1975). The Main Hinge marks the pinch out of facies D and E denoted by Skall (1975) in Figure 3.

3.0 TOPOGRAPHY AND DRAINAGE

The Pine Point Mine and surrounding area lie in the relatively flat lowlands of the GSL drainage area. The land generally slopes toward GSL in the north and is crossed by a number of small creeks and rivers which flow in the same direction. Low gravel ridges, muskeg areas, swamps and shallow lakes cover the area. The most prominent rivers are the Buffalo and Hay Rivers to the west of Pine Point and the Little Buffalo and Slave Rivers to the east. Surface topographic features are dominated by river activity where valleys have been eroded in the glacial deposits. Drainage is generally poor with swampy conditions prevailing. The climate is described as semi arid with approximately 33 cm of precipitation annually (Vogwill, 1976).

Surface water run-off originates as far south as the Caribou Mountains of northern Alberta, flowing north through a series of lakes and tributaries of which Buffalo Lake forms the largest lake south of GSL. Numerous small lakes dot the landscape, many of which are attributable to karst collapse structures. Surficial karst features such as sinkholes are numerous throughout the area.

The Pine Point town and mine area are located on a slightly raised portion of land paralleling the south shore of GSL which facilitates marginally better drainage conditions than encountered on a regional scale. Drainage is mostly north towards GSL with some run-off easterly towards Paulette Creek. The ridge is the location of the approximately 20 open pit mines of lateral dimensions from 120 to 900 metres and an average depth of 53 metres below land surface (Durston, 1979). The town and mine area lie approximately 60 metres above the level of GSL at a distance of some 10 kilometres from the south lake shore. The area between the

Pine Point mine and town and GSL is wet and characterized by springs representing major ground water discharge.

The Little Buffalo River Escarpment rises along the west shore of the Little Buffalo River from the Nyarling River to south of the Alberta border, reaching a maximum height of 49 metres just west of Fort Smith (Norris, 1965).

4.0 GROUND WATER FLOW

4.1 Regional Ground Water System

The Pine Point area is situated near the northeastern edge of of the Western Canada Sedimentary Basin. On the scale of the entire WCSB, the principal recharge area is generally considered to be the disturbed Foothills belt on the eastern slopes of the Rocky Mountains. Ground water flow occurs, at this scale, in a west and northwesterly direction, with major discharge occurring in the lowlands adjacent to the western margin of the Canadian Shield. Great Slave Lake represents a major lowland in this regional scale system and is considered a major ground water discharge area in the context of the WCSB.

Superimposed on the general ground water flow regime of the WCSB is a number of relative topographic highs which undoubtedly constitute significant secondary recharge areas to the basin flow system. These topographic highs include the Cypress Hills and Coteau Hills in the south and the Swan Hills, Clear Hills, Cameron Hills and Caribou Mountains in the north. Of these, the Caribou Mountains and, secondarily, the Cameron Hills probably have significant effects on the regional ground water system in the Pine Point area.

Examination of topographic maps and the literature concerning ground water flow in the WCSB rapidly leads to the conclusion that the Caribou Mountains and perhaps Cameron Hills represent recharge areas of significance to the Pine Point study area. They rise some 600 metres above the surrounding land surface and are separated by the Hay River. The depth within the basin to which the effect of these highs is hydraulically significant is uncertain, however earlier studies (eg. Hitchon, 1969) indicate that ground water flow, in at least the upper few thousand feet of sediments, is more or less radially distributed around the Caribou Mountains. The Cameron Hills apparently did not have sufficient data to have been included in the analysis conducted by Hitchon (op. cit.), however considering their elevation and extent, a similar effect can be expected. These topographic highs, superimposed on the WCSB flow system, may possibly deflect some ground water flow which originates in the Foothills belt away from the Pine Point area. It can further be postulated that discharge from the Cameron Hills to the Hay River serves to moderate the effect which the Cameron Hills may have on the deeper ground water system in the Pine Point area.

The main ground water discharge areas within the study area are clearly Great Slave Lake, the Little Buffalo River, and to some extent, the Slave River. The escarpment in the vicinity of the Little Buffalo River is the outcrop of the Keg River Formation, a relatively extensive carbonate aquifer which underlies the ore-bearing reef, Muskeg Evaporites and Buffalo River Shales. The underlying Chinchaga evaporites, which are considered less permeable than the overlying Keg River Formation, subcrop to the muskeg region of the Slave River.

The regional conceptualization of the ground water system is shown schematically in Figure 9. The following discussion provides background and details on the information and reports which lead to the schematic flow system presented in Figure 9.

Brandon (1964) collected evidence of major ground water discharge in the Great Slave Lake area through field observations of springs and from the chemistry of river waters. Springs discharging mineralized ground water were observed along the south shore of GSL at High Point, Sulphur Point and Windy Point. Springs were also observed at the mouth of the Salt River and at the base of the Little Buffalo River Formation escarpment. Brandon (op. cit.) noted that large quantities of ground water were discharged to the Slave River creating high specific conductance readings during low flow periods. Through chemical and isotopic analysis of water samples, in conjunction with surface run-off measurements, the presence of discharge zones was confirmed along the Salt, Slave, and Little Buffalo Rivers to the east, along Great Slave Lake between Fish Point and Presqu'ile Point and along the lower Buffalo River (Weyer, 1982). Discharge was also located along the Buffalo River where it turns north (Weyer, 1978). Sulphurous springs as well as artesian boreholes were observed along the banks of the Buffalo River from approximately 1.6 kilometres north of the highway bridge (see Figure 5) to the river's mouth (Weyer, 1982).

Ground water discharge areas are also evident through the presence of swampy areas, springs, and alkali flats. Ground water discharge maintains the swampy areas to the west of the Little Buffalo River both within Wood Buffalo National Park and between the Park and Pine Point (Weyer, 1982). Wet areas, as seen on air photos and LANDSAT imagery (some showing salt deposition), exist along the south shore of GSL and to the south and southeast of the Pine Point mine townsite in the headwaters of Hanbury Creek, and between the Pine Point ridge and GSL. Sulphur springs were observed between Angus Tower and Pine Point and near Angus Tower (Weyer, 1978). Artesian conditions in the form of violent blow-outs were encountered during exploration drilling in the Hay River valley approximately 19 kilometres south of GSL during 1922 and 1930. Brandon (1964) also noted the occurrence of artesian wells along the south shore of GSL.

The most significant ground water recharge area in the Pine Point region is the topographic high formed by the Caribou Mountains. The related discharge likely occurs along the Hay, Buffalo, Little Buffalo and Slave Rivers and into Great Slave Lake. This flow system, the bounds of which can be inferred from topography and surface hydrology to include the Hay River to the west, the Slave River to the east, Great Slave Lake to the north and the Caribou Mountains to the south, is significant in the upper geologic units of the GSL region.

Hitchon (1969) suggests that the Caribou Mountains act as a "major regional recharge area" in the WCSB and shows fluid potentials in the upper few thousand feet decreasing radially away from the area. However, the predominantly shale formations of the Caribou Mountains may hamper recharge rates to bedrock unless hydraulic communication is provided through discrete fractures or fracture networks. The results of the modeling study discussed in section 5 suggest that flow in the deeper sediments, in particular in the barrier reef complex, is not dominated by the recharge from the Caribou Mountains.

Ground water movement northerly from the Caribou Mountains towards GSL is likely slightly updip in the near surface bedrock formations of the interbedded shale, limestone and sandstone of the Hay River Formation, the Slave River limestones and the Muskeg River anhydrites. Flow direction in older units are likely less affected and probably dominated by the larger scale WCSB regional system. Brandon (1964) stated that the "movement of groundwater is through sinkholes, solution channels, and joints in the Middle Devonian and Ordovician rocks". This observation was mainly in response to observations of sinkholes in the Nyarling Valley on the road from Pine Point to Fort Smith in the Slave River, Muskeg and Keg River Formations (GSC, 1974; RCA, 1970). The joint pattern consists of two sets of joints oriented at N20°W and N70°E that are perpendicular to the bedding within the sedimentary strata (Norris, D.K., personal communication, as referenced in Brandon, 1964).

4.2 Local Ground Water System in the Mine Vicinity

The complex geology of the immediate Pine Point area has also resulted in an inherently complex ground water conveyance network. The barrier reef complex is clearly the most permeable and significant hydrogeologic unit in the area. Within the barrier reef complex, ground water is conveyed by three primary routes that vary significantly from the regional patterns. These are: (1) through the higher relative hydraulic conductivity facies, (2) through open solution channels and karstic features and/or former solution channels which are now filled with high relative conductivity media, and (3) along joint sets.

The relative hydraulic conductivities of the different facies were expressed qualitatively by Kyle (1981). In the lower barrier, Facies E (Figure 3) and to a lesser extent Facies D and B were identified as having the highest hydraulic conductivity, while in the upper barrier, the lower portion of Facies K (Presqu'ile Formation) was considered as highly permeable. Jackson and Beales (1966) observed that the "Presqu'ile dolostone is by far the most porous unit of the local stratigraphy" and that "solution along minor faults may have greatly increased the permeability."

Kyle (1981) suggests that the Chinchaga formation evaporites underlying the Keg River Formation and Pine Point barrier reef form an effective vertical barrier to ground water movement (Figure 3). Kyle (1981) also suggests that the intercalated shale and dense carbonate sequence of the Watt Mountain and Lower Slave Point Formation form a barrier to vertical ground water flow above the Pine Point Group. These observations suggest that ground water flow is predominantly in the Pine Point Group, especially the Presqu'ile Dolomite (Facies K) and that flow is confined by relatively impermeable formations below and above. Significant hydraulic continuity along the northeast-southwest trend of the reef is provided by the karstification, solution channeling and jointing characteristic of the reef. Any induced hydraulic changes (i.e. pumping and dewatering) will be most noticeable within the barrier reef complex, predominantly along the NE/SW trend. The shales to the north and evaporites to the south will likely serve as hydraulic boundaries. The underlying Keg River formation constitutes a regional aquifer which is connected to, although somewhat less permeable than, the barrier reef complex. The effects of dewatering will undoubtedly be evident in the Keg River Formation, although the extent of the drawdown will likely be considerably more limited than that observed in the barrier reef.

4.2.1 Karstification, Solution Channeling and Ore-Deposition in the Reef Complex

The occurrence of solution features in the barrier complex is quite erratic both laterally and vertically. The impact of solution features on the barrier ground water flow system is, of course quite pronounced, warranting a discussion of the development of the various groupings of solution features.

In the Pine Point mine area, two types of solution features have been encountered. These features have been delineated as a result of studies to explain the origin of the sulphide ore bodies (Skall, 1975; Kyle, 1981) which commonly form in the solution channels. High sulphide concentrations are found in: (1) large detritus-filled depressions near the disconformable surface at the top of the Presqu'ile Formation; and (2) in macropores and stratabound zones of increased permeability deeper in the Pine Point Formation which apparently lack direct contact with the disconformable surface.

Kyle (1981) interpreted the sulphide-rich macropores found in the lower part of the Presqu'ile (Facies K) in the upper barrier reef as being former caves and channels which formed in the upper phreatic zone during prolonged sub-aerial exposure to carbonate-deficient meteoric waters. Sulphide deposits are found in local collapses of the cave system in conjunction with breccia and other rubble which filled the voids upon collapse.

Areas of increased porosity and permeability were apparently formed adjacent to the zones of major dissolution, as evidenced from the presence of tabular type ore bodies (Kyle, 1981). These are most common along the Main Hinge area (Figure 4) in the lower Presqu'ile Formation and explain the presence of ore in the rock formations surrounding former solution features. The development of these zones of higher permeability was related to the availability of CO_2 in the ground water, explaining the limited lateral extent of the ore bodies.

Detritus zones, referred to as dolines (Kyle, 1981), are found in the limestone Facies C, D-2, H and I (Presqu'ile and Watt Mountain Formations) and tend to be elongated in a north-easterly direction parallel to the hinge zones, suggesting that karstification was controlled by the same structural disconformities which governed sedimentation. Dissolution of limestone was concentrated along joints and fractures oriented predominantly northwest. Dissolution continued vertically until ground waters were saturated with respect to calcite or until more resistant formations (ie. dolomite) were encountered. Slumping of the solution cavity walls occurred, filling the dolines with rubble. The remaining voids later acted as a host environment for ore formation.

A clear explanation of the nature and extent of the solution features in the lower portion of the reef (Pine Point Formation) has not been produced in past studies. Possible explanations (Kyle, 1981) include dissolution through: (1) extension of the intensively active dissolution from the upper barrier; (2) a mixing of fresh and salt water in this portion of the reef; and (3) sub-aerial exposure during a period prior to formation of the upper barrier.

Several studies (Jackson and Beales, 1966; Kesler et al., 1972; Kyle, 1981) have attempted to link the sulphide mineral deposition which characterizes the ore, to ground water flow patterns at the time of deposition. These studies found a close relationship between the location of the ore bodies and the orientation of and proximity to the hinge zones present in the area. Kyle (1981) suggested that "permeabilty zones subparallel to the N65°E trend of the hinges were formed." Jackson and Beales (1966) noted very minor faulting parallel to and associated with the hingings which "may well have been important in controlling subsequent solution and the improvement of porosity - permeability trends in the Presqu'ile dolostone".

Barnes and Czamanske (1967) as referenced in Kyle (1981) inferred that ground water flow was apparently from southeast to northwest at the time of mineral deposition based on relative solubilities for Fe, Zn and Pb sulphides. Significant fluid transport was considered to be updip, following the regional tilt (Kingspor, 1969) in the Pine Point barrier, and confined to the Presqu'ile Dolomite.

Kesler et al. (1972) correlated groundwater flow directions to the horizontal asymmetry of single crystals and crystal aggregates. These studies suggested a prominent flow direction along a path trending N50°E oriented parallel to the Presqu'ile Formation dip, with flow to the northeast dominating. Flow along paths southeast or nearly perpendicular to this trend were also delineated. Both of these flow directions correlate closely to the northeast and northwest orientation of the major vertical joint sets as observed in pits at Pine Point (Kesler et al., 1972). Two flow scenarios were developed as follows from these observations (Kesler et al, 1972):

(1) The net ground water flow direction was updip along the Presqu'ile Barrier Reef with local reversals and some flow to the southeast.

(2) The net ground water flow pattern was to the southeast with off-shoots along local joint sets to the northeast and southwest.

Kesler et al. (1972) favoured the first theory which agrees with opinions of others discussed previously.

4.3 Regional Karstification

Aerial photographs of the Pine Point area show hundreds of small lakes and ponds in the vicinity of the Pine Point Ridge which are karst and solution channel collapse features related to the barrier reef. Besides being common locally, these karst features are found regionally as well, implying significant karst development on a regional scale.

Irregular cavities, suggestive of widened joints and fissures as well as much larger sinkholes filled with the collapsed overlying formations, were noted in the Upper Slave Point Formation by Bayrock (1976). These were interpreted to indicate a prolonged time of erosion and karst development before Upper Devonian formations were deposited (Norris, 1963 as referenced in Bayrock, 1976).

The depth, lateral extent and nature of karstification in the south Great Slave Lake area is the subject of renewed interest in the past several years, commencing with the statements by Rhodes (1981) that "karsting ... has never (in the published literature) been given the prominence it deserves... many (collapse structures) penetrate very deep into the Pine Point Formation of the barrier and perhaps into the Keg River Formation, or even the

Chinchaga Formation". In a draft report Weyer (1982), based on reinterpretation of borehole logs and observations of sinkhole features on the surface, suggests that karstification and solution channeling is widespread through the area and may extend below the reef complex and Keg River Formation.

Some indication of the extent of karstification can be obtained by examining the multispectral LANDSAT imagery which covers a reasonably large area of the GSL region (Appendix II). It can be seen, by comparing these images to the geologic map in Figure 7 that the most extensive karstification occurs in the Hay River and Upper Slave Point Formations. Karst features such as sinkholes are not totally absent from areas underlain by the lower Slave Point, Keg River and Muskeg Formations, however they are certainly much less common. It is inferred from these observations that the main karstification in the area is limited to the Upper Slave Point and younger Paleozoic Formations. Karstification of the older Muskeg, Keg River and Chinchaga Formations does not appear very extensive.

The nature and extent of the karstification is of considerable interest and importance to an evaluation of the impact of mine dewatering on the ground water system. Unfortunately, there are no piezometric, permeability or other direct measurements on which to firmly establish the extent of the interformational hydraulic interconnection which might be provided by deep-seated karstification or solution channeling. Without any direct measurements or evidence to the contrary, the Chinchaga evaporites are considered to be a relatively low permeability non karstified lower boundary to the active ground water flow system in the area.

4.4 Hydrostratigraphic Interpretation and Hydraulic Properties

The hydrostratigraphic interpretation of the area, based on the reviewed data and reports, is provided below to provide a starting point for quantitative assessment of the regional affect of dewatering. As stated previously, the Chinchaga evaporites are considered the lower boundary of the active ground water flow regime. The overlying Keg River dolomite, with measured core permeabilities (Weyer 1982) of the order of 10^{-8} m/s, is the lowermost active hydrostratigraphic unit. Above the Keg River Formation lie (as stratigraphic equivalents) the Muskeg Evaporites in the south, the barrier reef as an isolated NE/SW trending high permeability unit, and the Buffalo River shales to the north. These three units are separate hydrostratigraphic units but occupy equivalent stratigraphic position in the "starting point" conceptualization. Overlying these units are the Watt Mountain and Slave Point Formations which are considered a low permeability upper boundary to the hydrogeologic system. This simplified hydrostratigraphy can be seen in Figure 12, which shows cross-sections through the study area.

The hydraulic properties of the barrier reef complex as measured from numerous pumping tests and operational records are presented in Table 2. The hydraulic conductivities of core materials of some of the other formations as measured by Weyer (1982) are presented in Table 3.

4.5 Dewatering Operations

The ore bodies at Pine Point are located in an area approximately 15 kilometres by 40 kilometres and at depths generally less than 100 metres (Calver, 1969). Prior to dewatering, ground water flowed through the area in a northeast direction towards GSL (Vogwill, 1976) as well as easterly to the Little Buffalo River. Water table contours (water levels in the reef complex) in the mine area prior to dewatering are shown in Figure 10. The reef is more or less unconfined in this area, with prepumping water levels corresponding approximately to bedrock surface.

Dewatering wells are located around the perimeter of the open pit mines, generally penetrating to approximately 60 metres below the pit bottom or 120 to 150 metres below land surface (Durston, 1979). The effect of dewatering on the local flow conditions is largely a function of pumping rate, ultimate drawdown, hydrogeological conditions and proximity to other dewatering operations.

An average of 50 to 60 pumps were operated per year in 5 or 6 pits in the years preceeding 1979 (Durston, 1979). Average annual deep well discharge rates are 60 million USGPD as of 1979 and are expected to increase to 100 million USGPD by 1985 (Durston, 1979). Well bores are drilled at 14.75 inches in diameter but many of the formerly-used 12.25 inch diameter wells exist. The discharge rates from the mine pits (1968-1982) and water levels in the mine area (1968-1982) are given in Tables 4 and 5 respectively.

Water from dewatering is discharged to perimeter ditches encompassing each open pit which drain by gravity through surface drainage channels to topographically lower areas. Recharge to the ground water system through the ditches is prevented or impeded by precipitation of carbonate and sulphate minerals in conjunction with the relatively low hydraulic conductivity of the overburden deposits. Loss of water from the ditches was estimated by Weyer (1982) at 0.4% over 1.5 kilometres.

5.0 GROUND WATER MODELING

The purpose of the ground water modeling study described in this section is simply to gain some insight and understanding into the regional controls on ground water flow, as well as to estimate the possible extent of influence of the dewatering. The model results are, of course, totally dependent on whether the conceptualization described previously is a reasonable representation. The modeled region is relatively large and the discretization is fairly coarse. However, it was considered instructive to attempt to quantitatively assimilate the limited data to obtain a first approximation of the regional flow regime and possible extent of the dewatering effects.

5.1 Boundary Conditions

The modeled region was selected on the basis of likely natural hydrogeologic boundaries (Figure 13). Great Slave Lake, as one of the major discharge areas for the Western Canada Sedimentary Basin, is defined as a constant pressure discharge boundary. Although the Hay River may effectively be a flow divide (at least in the upper formations), it was decided to include it in the modeled region for possible sensitivity studies. The Cameron Hills topographic high represents the western portion of the northern boundary. It is considered that ground water flow will be either parallel to this boundary, discharging to GSL, or that the topographic high of the Cameron Hills acts as a recharge flow divide for discharge to the Hay River. In both instances, the boundary is adequately represented by a Neumann-type zero flux boundary.

The eastern boundary of the modeled region is located along the Little Buffalo River Escarpment, which is clearly the principal discharge area for the Keg River Formation. The eastern boundary is represented as a prescribed pressure boundary allowing discharge to the Little Buffalo River.

The southern boundary corresponds to the topographic divide which is created by the Caribou Mountains. If ground water flow is considered to be more or less radially distributed around the Caribou Mountains, the southern boundary of the modeled flow region represents one of the radial flow lines.

The western boundary is the most difficult to represent, as it includes both the topographic highs of the Caribou Mountains and Cameron Hills as well as the relative topographic low of the Hay River. However, the initial conceptualization of the large-scale flow regime (Figure 9) illustrates the potential hydraulic barrier developed by these topographic highs, suggesting that there may be a flow divide, or more specifically a stagnation zone, in this area.

As a first approximation, the western boundary can be described as either a flow divide, or with prescribed pressures. Both alternatives allow water recharged in the Caribou Mountains and Cameron Hills to be discharged to the Hay River, however, the latter allows a flux across the boundary if the water balance in the modeled region so requires. It was considered more instructive, in the initial model runs, to prescribe pressures at this boundary and to examine the resulting flux across the boundary which would be required to obtain a water balance in the region. It the required flux is relatively small, then the possible flow divide created by the topographic highs may be inferred to be "first approximation" correct. This assumes, of course, that the assigned hydrogeologic parameters are also "first approximation" correct. In any event, the western boundary conditions can be varied to conform to different scenarios. It was considered most instructive to start with prescribed pressures in order to establish the extent of influence of the dewatering before deciding if the boundary should be alternatively represented.

The lower boundary of the modeled region is considered to be the relatively impermeable Chinchaga evaporites. The evaporites have, however, been incorporated in the model as a lower stratigraphic unit so as to allow flexibility in any further sensitivity studies. The upper boundary is considered to be the water table which, on first approximation, is represented in most areas by the topography.

The model is calibrated to the water table position by assigning areal recharge and discharge estimates. These estimates were obtained by first prescribing a water table position and then by obtaining the corresponding model-calculated recharge and discharge rates areally. For subsequent model simulations, the upper boundary is assigned as a flux boundary with the exception of Buffalo Lake and Great Slave Lake which are given prescribed pressures.

5.2 Hydrostratigraphic Units

The modeled region has been subdivided into hydrostratigraphic units. A hydrostratigraphic unit is a unit with considerable extent and possessing distinctive hydrogeologic properties continuous throughout the unit. The initial hydrostratigraphic interpretation was presented in section 4.4. Cross-sections through the modeled region illustrating the hydrostratigraphic units are presented in Figure 12. The units and their initial assigned permeabilities are

Table 6

• Chinchaga Evaporites	impermeable
• Keg River Dolomite	10^{-6} m/s
• Muskeg Evaporites	10^{-9} m/s
• Barrier Reef Complex	10^{-4} m/s

- Buffalo River Shales — 10^{-9} cm/s
- Slave Point Limestones, Shales — 10^{-9} cm/s
- Hay River (+Upper Fort Simpson) Shales, Siltstones, Limestone — 10^{-9} cm/s
- Cretaceous Shales, Siltstones Sandstones — 10^{-9} cm/s

This initial assignment of permeabilities essentially limits most of the active ground water flow system to the reef and Keg River dolomite, which is the initial simplified conceptualization. The permeability values (other than the reef) were selected to be within the generally accepted published ranges of values for these types of media. The reef permeability was assigned on the basis of existing data from pumping tests (Table 2). It was inferred, based on discharge along the Little Buffalo River Escarpment, that the permeability of the Keg River Formation was intermediate between the reef and the lower permeability confining units.

5.3 Steady-State Conditions Prior to Dewatering

The model was initially calibrated by assigning the boundary conditions discussed previously and running a steady-state simulation. The steady-state simulation alone resulted in several observations, the most interesting of which concern the internal water balance and areal distribution of recharge and discharge. The hydrostatic heads assigned on the western boundary essentially represent the maximum influences that the Caribou Mountains and Cameron Hills could have on the deep flow regime. If the net flux required to maintain a water balance in the modeled region had been small, it would have suggested that the topographic highs may possibly result in a flow barrier to deeper ground water derived from the Rocky Mountain Foothills belt recharge area. However, the calculation indicated that a net inward flux of the order of 20,000 m^3/day was required to maintain the internal water balance. Since the reef hydrostratigraphic unit is the most permeable unit, the bulk of the inward flux was into the reef. These observations suggest that the topographic highs, although important local recharge areas, may not dominate flow at depth. The significance of the barrier reef complex as a "drain" within the hydrogeologic system is also apparent from the steady-state simulations. Ground water flow directions in the units adjacent to and above the reef are generally towards the reef.

A second observation which can be made from the steady-state simulations is the areal distribution of recharge and discharge (Figure 14). With the initial boundary conditions of prescribed water table, a "recharge or discharge" flux is calculated by the model for each discretized gridded area. This value for recharge or discharge is not directly comparable to what is normally referred to as recharge due to infiltration. The calculated recharge or discharge is actually more correctly termed "subfiltration" or that amount of water entering or leaving the units below the very active local (shallow) ground water flow systems. Most "infiltration" recharge to the shallow subsurface is discharged in the local vicinity and does not influence the large scale regional system. Consequently, the calculated recharge and discharge rates for the modeled region are usually substantially smaller than those normally referred to as infiltration or discharge rates.

The distribution of regional system recharge and discharge from surface infiltration or discharge is illustrated in Figure 13. The largest recharge areas on surface are the topographic highs of the Caribou Mountains and Cameron Hills, however the flux across the western boundary into the reef at depth is significantly greater than the amount of water obtained from the topographic highs. A second major recharge area occurs in the reef vicinity south of GSL where there is a significant break in land surface elevation and the permeable reef is the uppermost unit. The land surface drops off significantly from this area to GSL, and the reef areas nearest the lake are discharge zones.

The recharge and discharge rates which are calculated from the steady state calibration runs are subsequently used as input for the transient simulations. At steady state the end result is clearly the same whether a fixed water table or calculated recharge/discharge rates are used, since the latter are calculated from the assigned water table. In the transient simulations, the water table is a free water surface that is allowed to respond to the pumping.

5.4 Response of Ground Water System to Dewatering Operations

The response of the ground water flow system due to pumping operations in the Pine Point Mines vicinity was simulated using the previous "steady-state" simulations as the initial conditions. The pumping records for the pits and millsite for the period 1965-82 are listed in Table 4. The pit and millsite discharges were grouped into two finite-difference grid blocks for model simulation purposes. Pits W-17 and X-15 were located in grid block (I7, J4) and the remaining pits and the millsite in (I6,J4).

Drawdown of the water table in 1978 and 1982 is illustrated in Figures 15 and 16. It is important to recall that the drawdowns are averaged over the full grid block in the illustration. The maximum drawdown near the pits will be somewhat greater than those shown on the Figures. However, at the large regional scale under investigation, the most important aspect is the volumetric removal of ground water from the region and the resulting large scale effects. The drawdown calculations are considered to only be first approximation correct, due to the coarse grid discretization and hydrostratigraphic simplification. Detailed studies with much finer discretization can be easily developed from the regional modeling study.

The maximum drawdown of the water table is of the order of 22 metres in the reef vicinity (recalling the grid block averaging discussed above) while the lateral extent of 1 metre drawdown appears limited to the ridge of the reef. These results suggest that water table elevations should remain relatively unaffected beyond the reef boundaries while substantial effects will be seen (and have been measured) in the unconfined reef vicinity on and near the mine properties.

Drawdowns within the reef and the adjacent Buffalo River shales and Muskeg evaporites for 1978 and 1982 (Figures 17 and 18) show that the reef is significantly affected within the mine properties, however effects diminish to 1 metre or less drawdown within 10 to 15 kilometres along the plunge of the reef in both the updip and downdip directions. There is some uncertainty on Figure 18 concerning the western extent of the drawdown, likely due to effects resulting from coarse vertical discretization in this area. These effects could be eliminated in a more detailed study.

None of the confining units, other than the Keg River dolomite immediately below the reef, show any significant (>1m) drawdowns. The Keg River exhibits similar drawdowns to those of the reef immediately below the reef; however, there is no lateral extension of these drawdowns in the Keg River beyond the reef boundaries. The Muskeg evaporites and Buffalo River shales, lateral stratigraphic equivalents of the reef, show no response, nor do the overlying Slave Point and Hay River shales.

The basic conclusion which can be drawn from these first approximation model calculations is that the water pumped from the reef for dewatering is virtually all derived from the high permeability, elongated reef unit. A small percentage is probably derived from the underlying Keg River Formation. It seems unlikely that significant effects will be seen in any of the hydrostratigraphic units much beyond the lateral extent of the reef.

6.0 CONCLUSIONS

1. Great Slave Lake and the Little Buffalo River are the principal ground water discharge areas for flow within the portion of the Western Canada Sedimentary Basin which underlies the study area (Caribou Mountains to Great Slave Lake).

2. Although the Caribou Mountains and Cameron Hills are significant local recharge areas, it appears unlikely that they intercept or divert ground water flow at depth in the Western Canada Sedimentary Basin. Most of the ground water flow in the deep units, particularly the Pine Point Barrier Reef Complex, appears to be derived from regional ground water recharge in the Rocky Mountain Foothills belt.

3. Extensive regional karstification, based on LANDSAT imagery and airphoto interpretation, appears limited to the Upper Slave Point and Younger Paleozoic Formations. This does not exclude limited karstification of the older units, but significant interformational flow does not appear likely.

4. Using a simplified hydrostratigraphic conceptualization, which basically considers the Pine Point Barrier Reef Complex a high permeability unit (10^{-4} m/s) underlain by the less permeable Keg River dolomite (10^{-6} m/s) and confined laterally and above by the Muskeg Evaporites, Buffalo River Shales and Slave Point Shales/Limestone (all at 10^{-9} m/s) respectively, a first approximation 3-dimensional ground water flow model was used to evaluate the large scale flow regime in the region and to estimate the regional effects of Pine Point mine dewatering operations. The reef unit is capable of providing virtually all the pumped water, with a small percentage likely derived from the Keg River Formation. Drawdown effects in all Formations are virtually limited to the vicinity of the reef complex.

5. The drawdown contour map in 1978 suggests that large drawdown effects are concentrated in the 35 km x 8 km area containing the pits. Ground water levels between the pits and Great Slave Lake are higher than the water level of Great Slave Lake, indicating the Lake is not a source of pumped water.

6. Information from mine personnel on water levels and ground water chemistry further to the west in the Pine Point Barrier Reef Complex indicate that the flow is from west to east, with a gradient of approximately 2.4×10^{-3}, and that the water within the reef complex is highly mineralized and sulfurous. The water pumped from the pits is substantially less mineralized, suggesting that a good deal of the pumped water may be derived from local recharge to the unconfined subcropping reef complex. This is consistent with the distribution of recharge and discharge areas calculated in the modeling studies.

7.0 RECOMMENDATIONS

A more detailed modeling study with field verification in the mine vicinity would allow much finer grid discretization and much more quantitative estimates of potential dewatering effects beyond the reef boundaries. The coarse grid discretization requires averaging of drawdown over relatively large areas, resulting in the "first approximation" assessment provided herein.

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TABLE 1. Detailed Givetion Stratigraphy of the Pine Point Barrier Reef (modified from Kyle (1981) after Skall (1975) and Adams (1975))

Age	Formation	Facies	Maximum Thickness (meters)	Description
LATE GIVETIAN	SLAVE POINT	P	12	Limestone, dark brown, dense micrite, slightly argillaceous, interclasts common
		O	50	Limestone, light to dark brown, micrite or sand, large interclasts common, slightly argillaceous to common shaley laminae, burrowed
		N	18	Limestone, often dolomitic, light gray, dense micrite; blotchy bedding, stromatolite, and fenestrate structures common
		M	10	1. Shale, gray to blue-gray, usually calcareous and mottled with disseminated sulfides 2. Limestone or dolostone, light to medium brown, sand or micrite, argillaceous
	WATT MOUNTAIN	L	45	Limestone, may be dolostone or dolomitic; very light gray, light gray, buff, light green gray; micrite with minor sandy beds; laminite, stromatilite, blotchy bedding and fenestrate structures common; minor gypsum; waxy green shale interbeds
MIDDLE GIVETIAN (discon-formity)	PINE POINT GROUP	K	65	Dolostone, buff to light gray, coarse-crystalline, often with large vugs; uniform granular, mottled, zebra and breccia-moldic textures common; white dolomite may be abundant

Age	Formation	Facies	Maximum Thickness (meters)	Description
MIDDLE GIVETIAN (con't)	PINE POINT GROUP (con't)	Muskeg formation	120	Anhydrite and gypsum, white to light brown, dense; massive laminated, and nodular bedding; may be interbedded with J facies dolostone
		J	145	1. Dolostone, light gray to blue-gray, dense to sucrosic; laminite, blotchy bedding, stromatolite and fenestrate structures common 2. Dolostone, light to medium brown, sucrosic with intergranular porosity; slightly argillaceous to laminated 3. Dolostone, light brown to buff, sucrosic to sandy with good intergranular porosity; some faint argillaceous wisps 4. Dolostone, buff to medium brown, sucrosic with some argillaceous wisps, may be vuggy 5. Dolostone, very light gray, dense micrite
		I	30	Limestone, very light gray, pelleted micrite and sand; fenestrate, laminite, and stromatolite structures common
		H		Limestone, very light gray, micrite with bioclastic debris

Age	Formation	Facies	Maximum Thickness (meters)	Description
MIDDLE GIVETIAN (con't)	PINE POINT (con't)	G	60	Shale, dark gray to blue-gray, fissile, calcareous, disseminated iron sulfides
		F	35	Limestone, occasionally dolmitic, dark brown to black, dense micrite, very bituminous and argillaceous
		E	45	Dolostone, buff to light brown, sucrosic to sandy with good intergranular porosity, often friable; lacks argillaceous material
		D	30	1. Dolostone, light brown to buff, sucrosic to sandy matrix with abundant fossils; may have large vugs and good intergranular porosity 2. Limestone, very light gray, skeletal sand and clasts cemented by sparry calcite 3. Dolostone, buff to blue-gray, dense, fragmental (often vague due to diagenetic modifications)
		C	20	Limestone, buff to very light gray, micrite and bioclastic sand; lacks argillaceous material
		B	60	1. Dolostone, rarely limestone, light to medium gray-brown, sandy to sucrosic, slightly argillaceous

Age	Formation	Facies	Maximum Thickness (meters)	Description
				2. Dolostone, rarely limestone, medium to dark gray-brown to black, dense to sucrosic, very argillaceous, common chert nodules and secondary silicification
				3. Dolostone, light to medium brown, sandy to dense matrix with zones of good intergranular pososity; many large vugs after leached fossils
EARLY GIVETIAN	KEG RIVER	A	70	Dolostone and limestone, medium to dark brown, dense to sucrosic, varying amounts of argillaceous and carbonaceous wisps, minor chert nodules, E-shale marker beds (1 to 3) occur 35 to 50 meters above base

TABLE 2. Hydraulic Properties of the Pine Point Barrier Reef Complex

Pit	Transmissivity USGPD/FT	Transmissivity m^2/s	Storativity	Source
X-15	35,000	0.0050	0.006	1
J-44	60,000	0.0086	0.025	1
O-42	72,000	0.0103	0.035	1
N-42	54,000	0.0078	0.016	1
K-57	41,000	0.0059	0.001	1
A-70	65,000	0.0093	0.002	1
W-17	69,000	0.0099	0.05	1
K-62	69,000	0.0099	0.05	1
Hinge Zone #1	90,000	0.0129	0.03	1
R-61	37,000	0.0053	0.001	1
J-70	70,000	0.0101	0.002	1
A-55	70,000	0.0101	0.04	1
A-55	52,412	0.0075	0.012	1
Western Mines Jan/79	182,595	0.0262	0.0029	1
K-77	128,818	0.0185	0.0062	1
Hinge Zone #2	76,123	0.0109	0.03397	1
M-40	50,000	0.0072	0.016	1
T-58	76,000	0.0109	0.00064	1
M-64	116,000	0.0167	0.038	1
J-69	70,000	0.0100	0.050	2
X-25 (Westmin Resources)	115,000	0.0165	-	3
R-190 (Westmin Resources)	869,615	0.125	-	4
Millsite	185,000	0.0266	-	5
	90,000-100,000	0.0129 - 0.0144	-	6
Townsite	17,000	0.0024	-	6

Data Sources:

1. Pine Point Mines (1983)
2. Durston (1979)
3. Golder (1979) as referenced in Weyer (1982)
4. Golder (1980) as referenced in in Weyer (1982)
5. Hills (1977) as referenced in Weyer (1982)
6. Vogwill (1976)

TABLE 3. Hydraulic Conductivities Measured in Rock Cores of CDR-74 (from Weyer, 1982)

Formation	Hydraulic Conductivity (cm/s)	Average Hydraulic Conductivity (cm/s)
Hay River	3.15×10^{-9}	3.15×10^{-9}
Watt Mountain	7.69×10^{-9}	7.69×10^{-9}
Muskeg	1.3×10^{-9} 3.35×10^{-9}	2.3×10^{-9}
Upper Keg River	7.02×10^{-7} 3.28×10^{-5} 4.63×10^{-7} 1.05×10^{-6} 3.18×10^{-8} 7.29×10^{-6} 8.16×10^{-8}	6.1×10^{-6}
Lower Keg River	6.03×10^{-9} 1.04×10^{-8} 1.3×10^{-8}	9.8×10^{-9}

TABLE 4. Discharge Rates (m^3/day) From Pits and Millsite During Years 1968-1982

PIT	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982
J-44		34,065	38,425	33,068	40,197										
N-42	13,735	7,522	4,088												
O-42	3,924	23,164	29,705	16,351	14,389										
X-15	3,270	18,422	23,873	26,707	25,710	14,760				1,395	10,001	10,426			
K-57				21,622	20,755	37,377	38,153	47,353							
M-40					12,378	6,088	3,575								
W-17					37,281	53,959	90,793	106,921	116,911	115,507	64,495	29,724			
R-61						3,270	4,360	9,266	25,252	50,287	49,061	46,843	36,433		
K-62								31,536	38,246						
A-70									31,553	53,557		57,993	104,373	67,493	
J-69										6,355	63,852	78,823			
T-58										23,353	51,617	4,393			
S-65											6,355	6,747	14,557		
A-55											850	1,221	47,976	109,589	131,150
K-77														18,388	33,841
M-64														2,202	30,083
N-81															2,029
Mill	12,500	16,400	17,000	17,000	17,000	17,000	17,000	17,000	17,300	18,400	18,700	18,000	17,600	20,800	19,200
TOTAL	33,429	99,573	113,091	114,748	167,710	132,454	153,881	212,076	229,262	268,854	264,931	254,170	220,939	218,472	216,303

Note: Millsite discharge estimated at 9,500 m^3/day during 1965-68

TABLE 5. Water Levels (feet) and Drawdowns (feet) During Years 1968-1982

PIT	PREPUMPING 1968-69	1970	1972	1974	1976	JAN. 1 1977	DEC. 31 1977	1978	JAN 1979	DEC 1979	DEC 1980	DEC 1981	DEC 1982
J-44	627	548 (79)	569 (58)		568 (59)			560 (67)					
N-42	632	584 (48)	574 (58)	589 (43)	583 (49)			560 (72)					
O-42	635	590 (45)	578 (57)	600 (35)	592 (43)			565 (70)					
X-15	610	560 (50)	550 (60)	515 (95)	475 (135)	469 (141)	452 (158)	478 (132)	429 (181)	501 (109)	521 (89)	535 (75)	541 (69)
K-57	656	595 (61)	595 (61)	531 (125)	555 (101)			579 (77)	583 (73)	567 (89)	553 (103)	535 (121)	517 (139)
M-40	625	580 (45)	571 (54)	580 (45)	575 (50)			580 (45)					
W-17	619	595 (24)	578 (41)	470 (149)	410 (209)	392 (227)	380 (239)	460 (159)	399 (220)	512 (107)	540 (79)	549 (70)	555 (64)
R-61	710			715 (-5)	660 (50)	652 (58)	616 (94)	608 (102)	594 (116)	618 (92)	670 (40)		662 (48)
K-62	652	625 (27)	613 (39)	591 (61)	524 (128)			576 (76)			547 (105)	535 (117)	531 (121)
A-70	607	581 (26)	603 (4)		532 (75)	508 (99)	487 (120)	570 (37)	574 (33)	435 (172)	386 (221)	483 (124)	504 (103)
J-69	662	656 (6)	655 (7)		616 (46)	606 (56)	571 (91)	560 (102)	513 (149)	569 (93)	579 (83)	568 (94)	574 (88)

PIT	PREPUMPING 1968-69	1970	1972	1974	1976	JAN. 1 1977	DEC. 31 1977	1978	JAN 1979	DEC 1979	DEC 1980	DEC 1981	DEC 1982
T-58	719			710 (9)	711 (8)	698 (21)	636 (83)	627 (92)	607 (112)	673 (46)	688 (31)		689 (30)
S-65	708					669 (39)	647 (61)	628 (80)	641 (67)	652 (56)	675 (33)		667 (41)
A-55	615					572 (43)	565 (50)		574 (41)	542 (73)	438 (177)	359 (256)	295 (320)
K-77	672							610 (62)			595 (77)	550 (122)	605 (67)
M-64	672	670 (2)	651 (21)		552 (120)			580 (92)				573 (99)	572 (100)
Millsite	610	555 (55)	568 (42)		558 (52)			550 (60)	560 (50)	556 (54)	549 (61)	535 (75)	524 (86)
N-81	686												655 (31)
W-85	585												569 (16)
Z-64	600											465 (135)	475 (125)

Notes:
- Drawdowns are shown in brackets
- 1968/69 water levels estimated from drawing "Original Water Table Contours (1968 and 1969) and all Test Holes" by PPM
- 1970, 1972, 1974, 1976 and 1978 water levels estimated from drawings of "Groundwater Contours" by PPM
- 1977, 1979, 1980, 1981 and 1982 water levels obtained from tabulated data from PPM

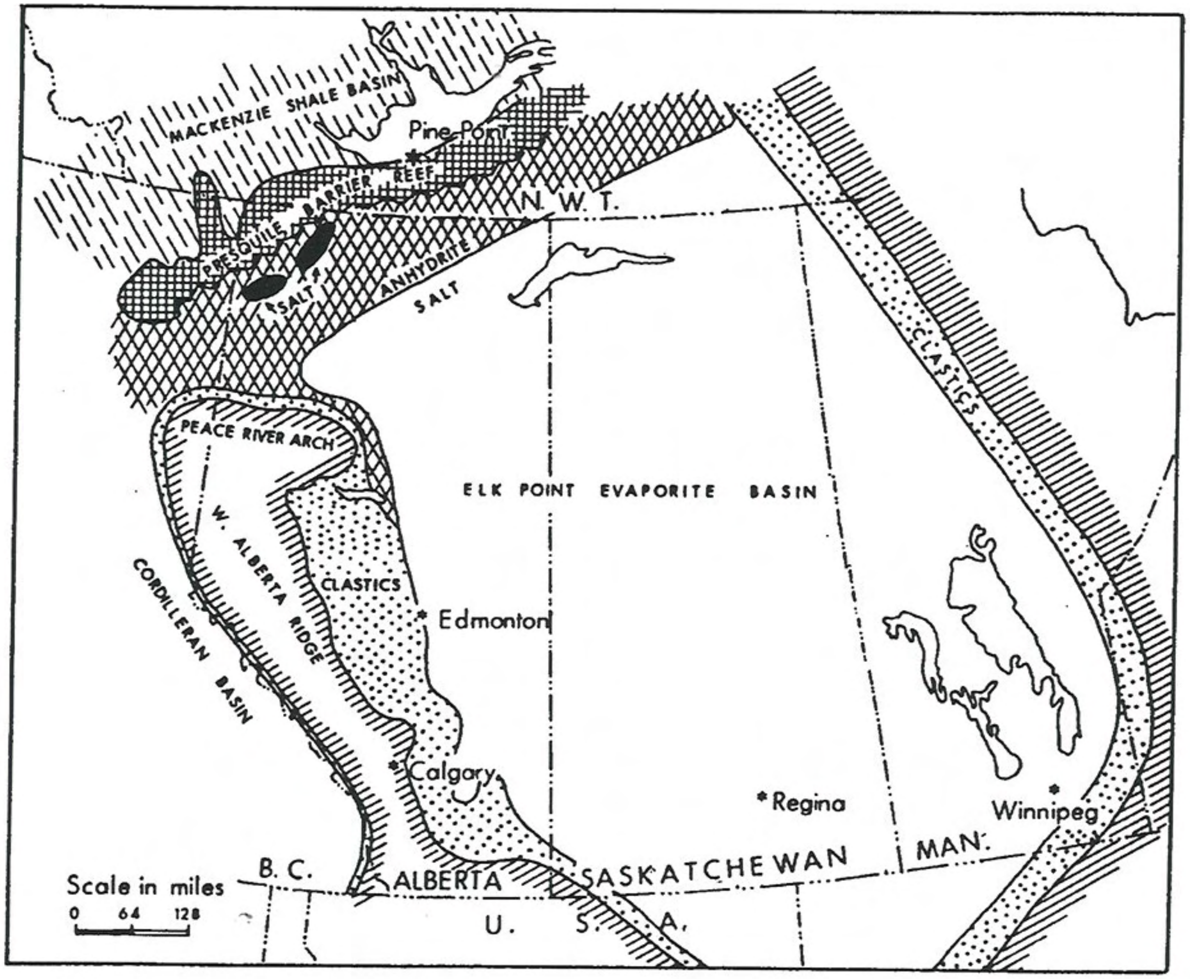
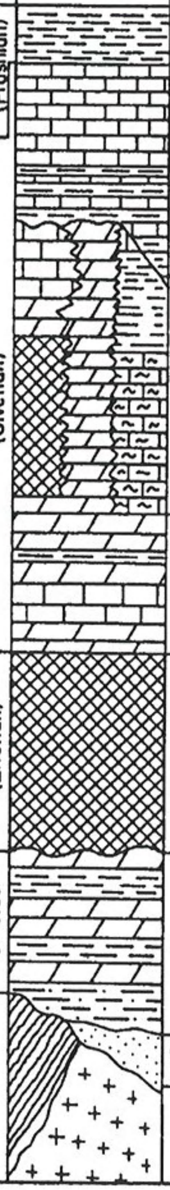


Figure 1. General formational conditions of the Pine Point barrier complex (from Jackson and Folinsbee, 1969; modified from Grayston, Sherwin and Allan, 1964)



AGE	STRATIGRAPHY	FORMATION	THICKNESS (meters)	DESCRIPTION
U. DEVONIAN (Frasnian)		HAY RIVER		Calcareous shale, minor limestone
		SLAVE POINT	50-70	Argillaceous limestone, minor dolostone, calcareous mudstone
M. DEVONIAN (Givetian)		WATT MOUNTAIN	15-45	Limestone and dolostone, waxy green mudstone interbeds
		PINE POINT GROUP	75-150	Upper — Limestone of reefal and associated depositional facies; extensive coarse-crystalline dolostone (Presqu'ile); transitional into calcareous shale (Buffalo River Fm.) to NW Lower — Fine-crystalline dolostones of reefal and associated depositial facies; transitional into bituminous limestone to NW and evaporites (Muskeg Fm.) to SE
		KEG RIVER	65-75	Argillaceous dolostone and limestone
M. DEVONIAN (Eifelian)		CHINCHAGA	90-110	Anhydrite and gypsum, minor dolostone, limestone, and mudstone
ORDOVICIAN or older		MIRAGE POINT	60-90	Dolostone, mudstone, siltstone, anhydrite, and gypsum
PRECAMBRIAN		OLD FORT ISLAND	0-30	Friable, fine to medium-grained sandstone
				Micaceous quartzite and granodiorite ?

Figure 2. Stratigraphic column of the Paleozoic formations in the Pine Point area (from Kyle, 1981; after Norris, 1965 and Skall, 1975)

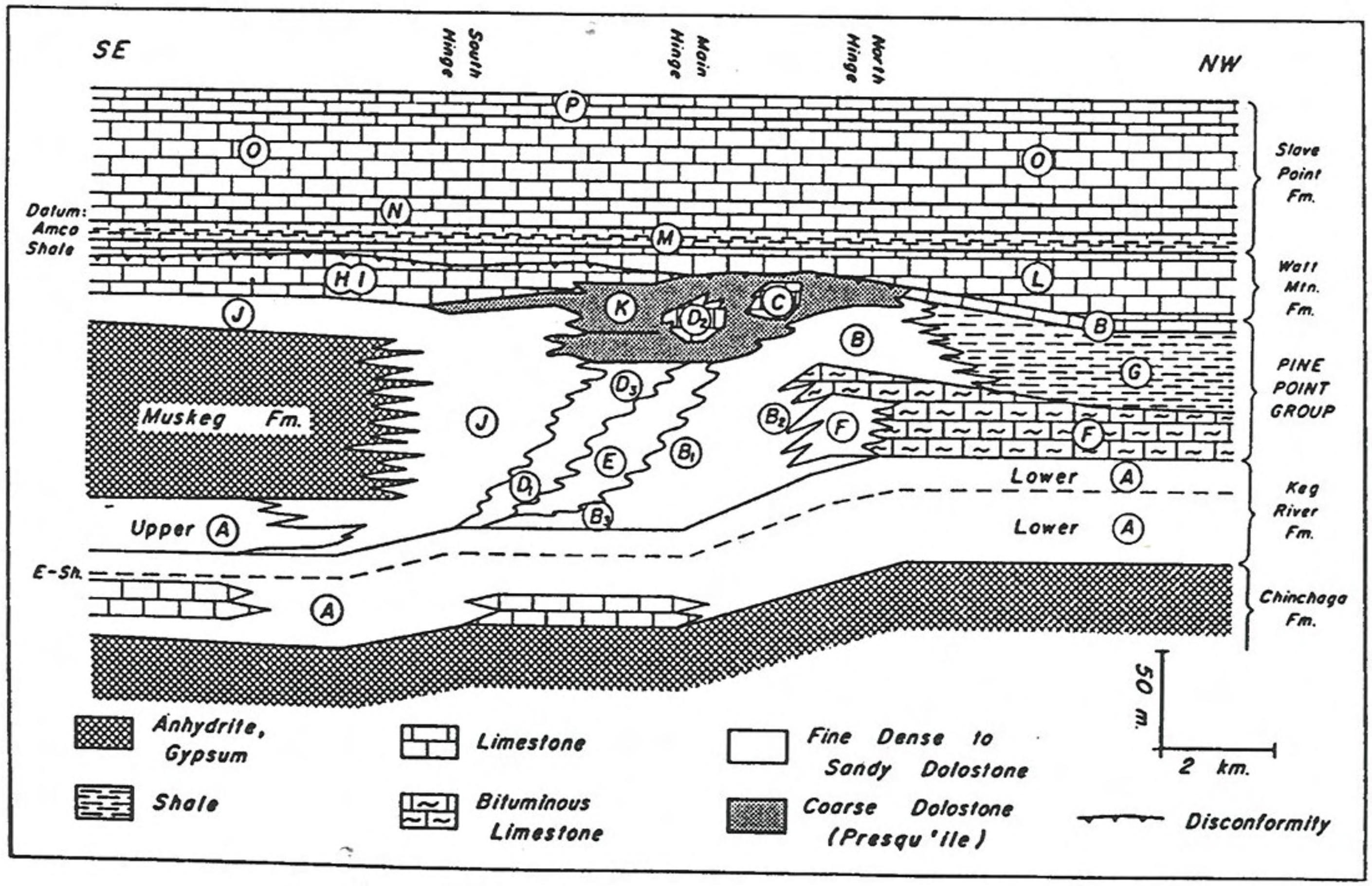


Figure 3. Cross-section of the Pine Point barrier reef showing lithofacies (from Kyle, 1981; modified after Skall, 1975)

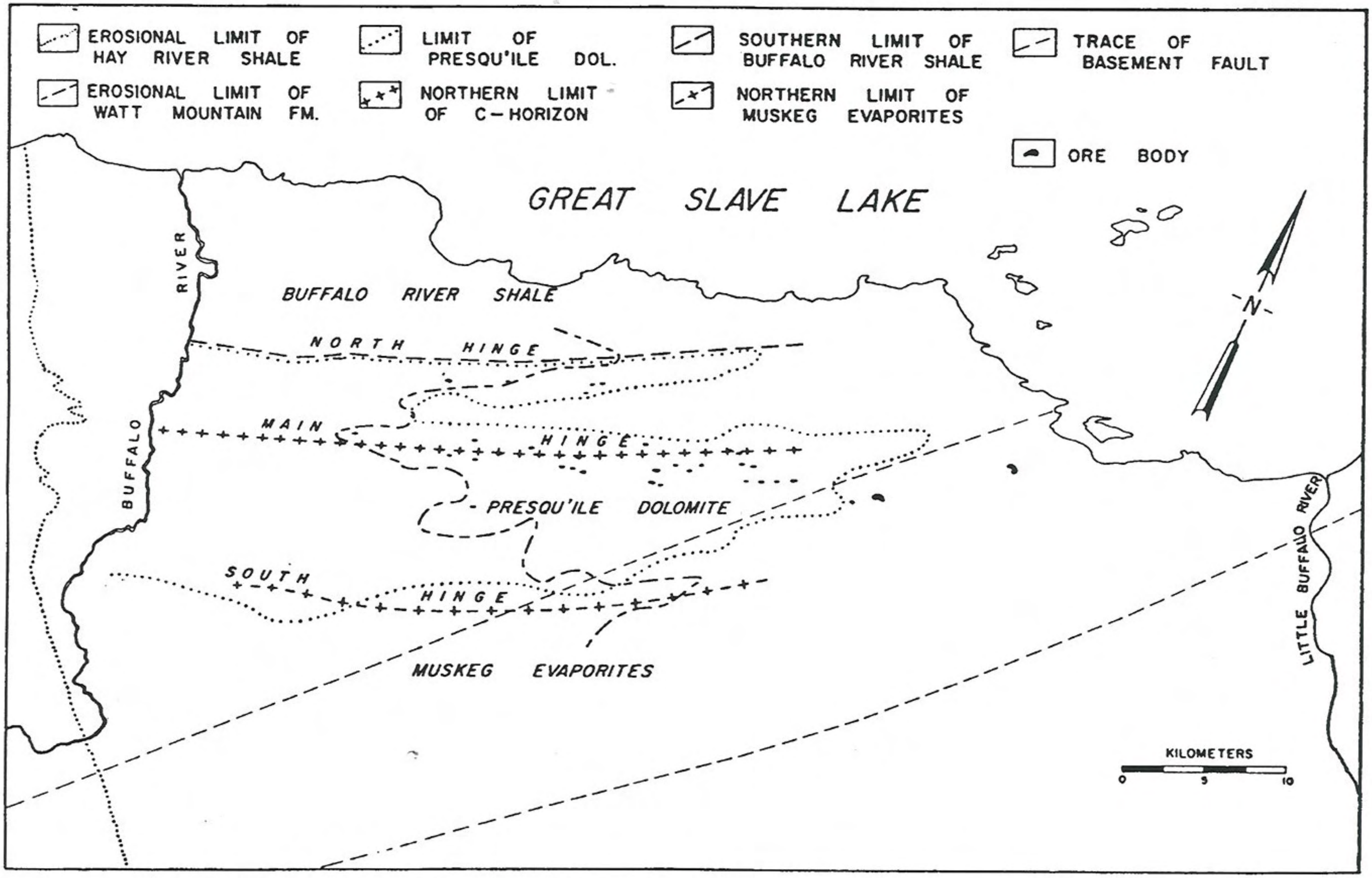


Figure 4. Major geologic features of the Pine Point mining district (adapted from Kyle, 1981; modified after Skall 1975, Norris, 1965, and Pine Point Mines Ltd., 1983)

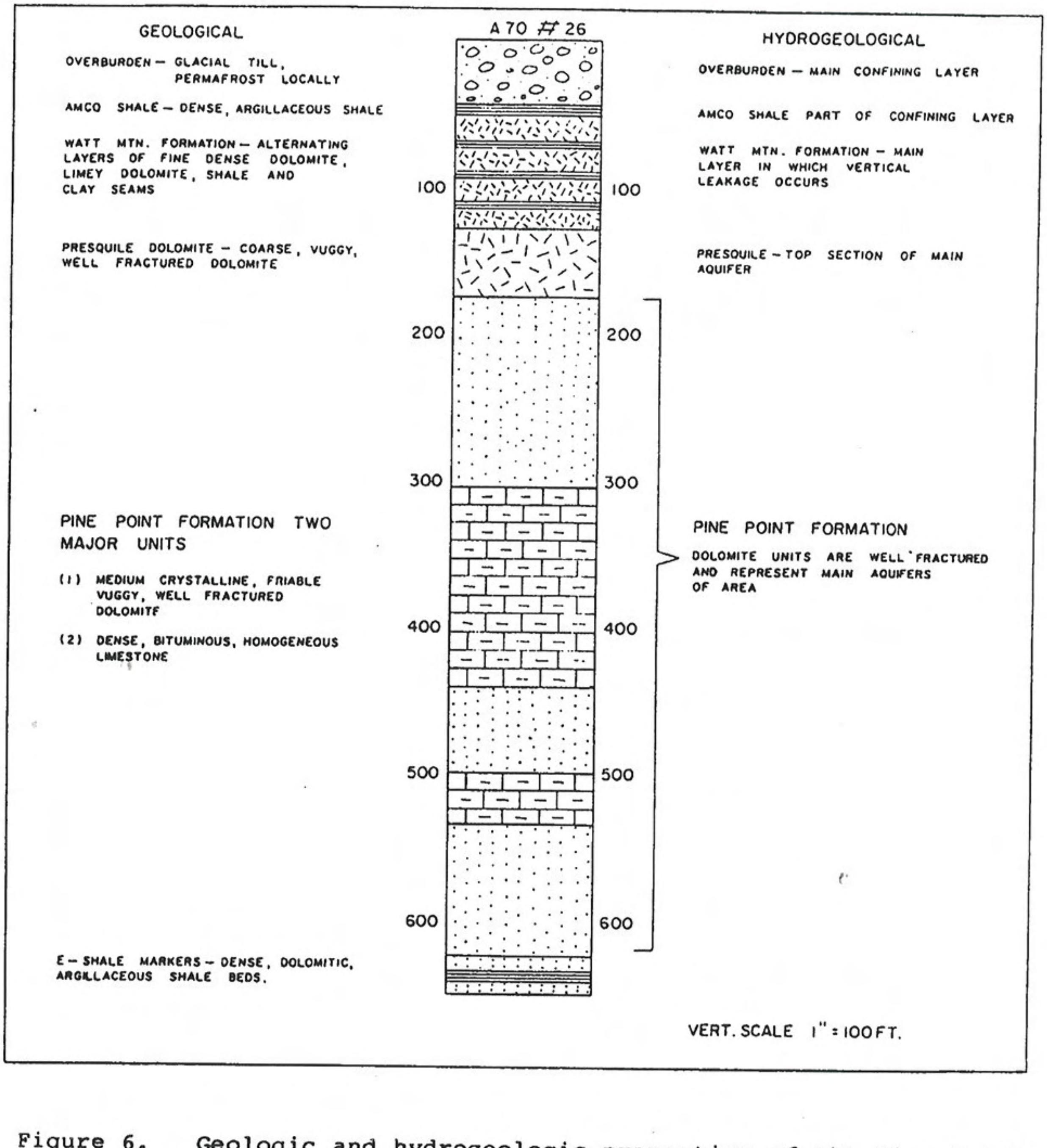


Figure 6. Geologic and hydrogeologic properties of the Pine Point barrier complex at the A-70 pit area (from Vogwill, 1976)

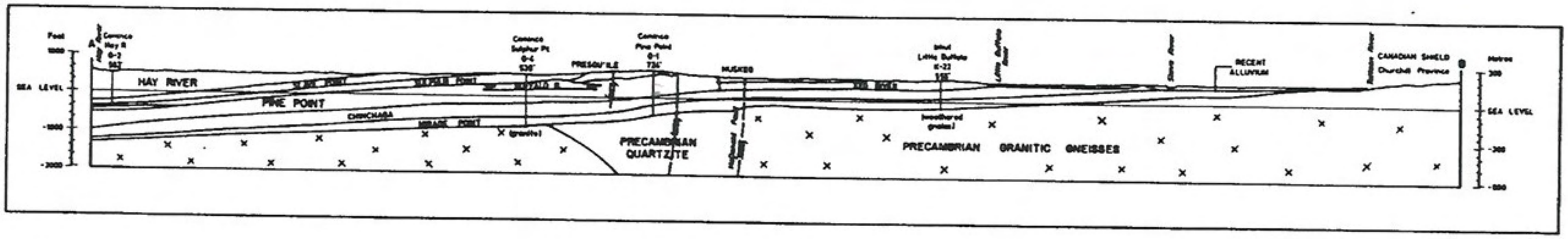


Figure 8. Geologic cross-section from NE to SW south of Great Slave Lake (from GSC, 1974)

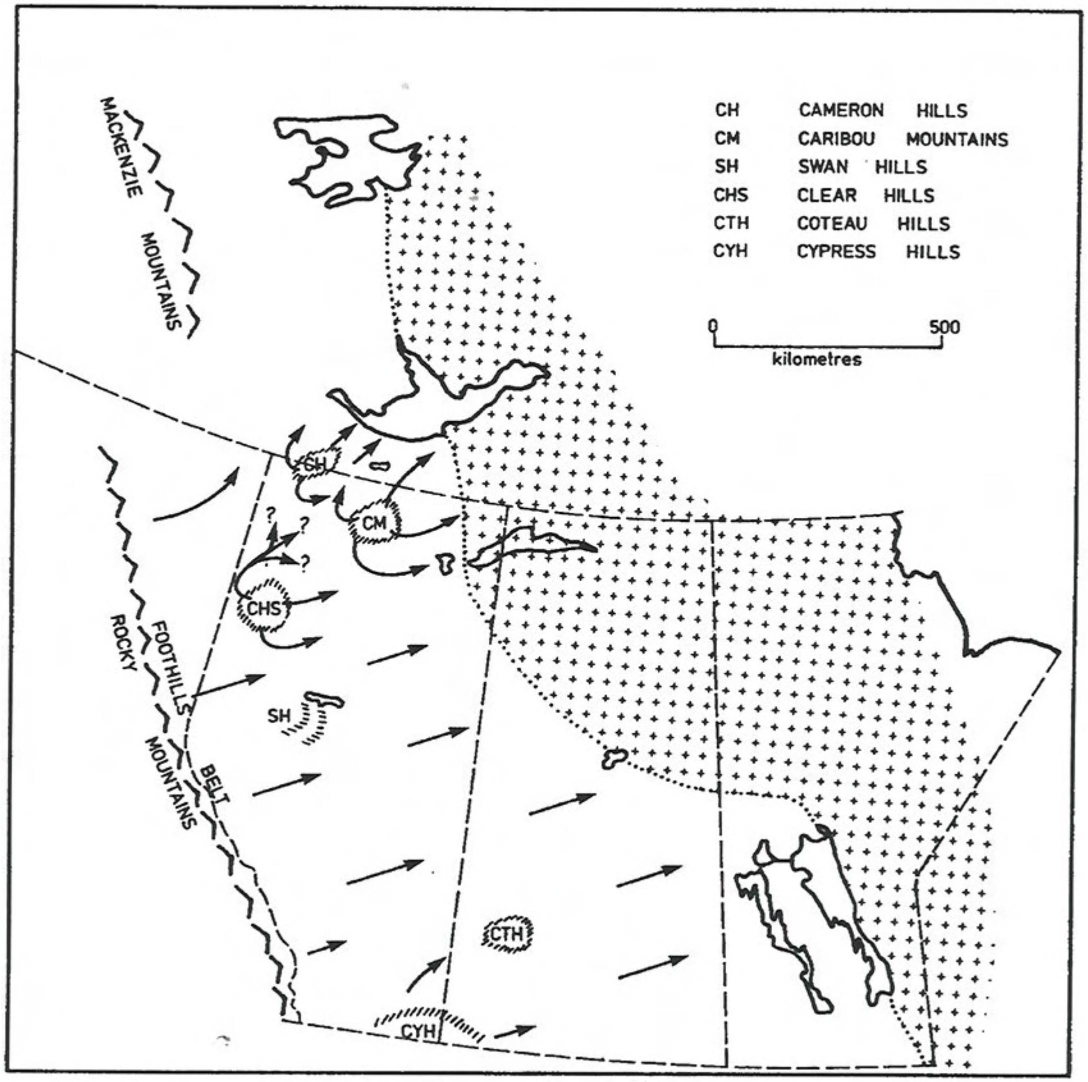


Figure 9. Schematic of Western Canada Sedimentary Basin ground water flow directions showing influence of Caribou Mountains and Cameron Hills on Regional Flow Regime

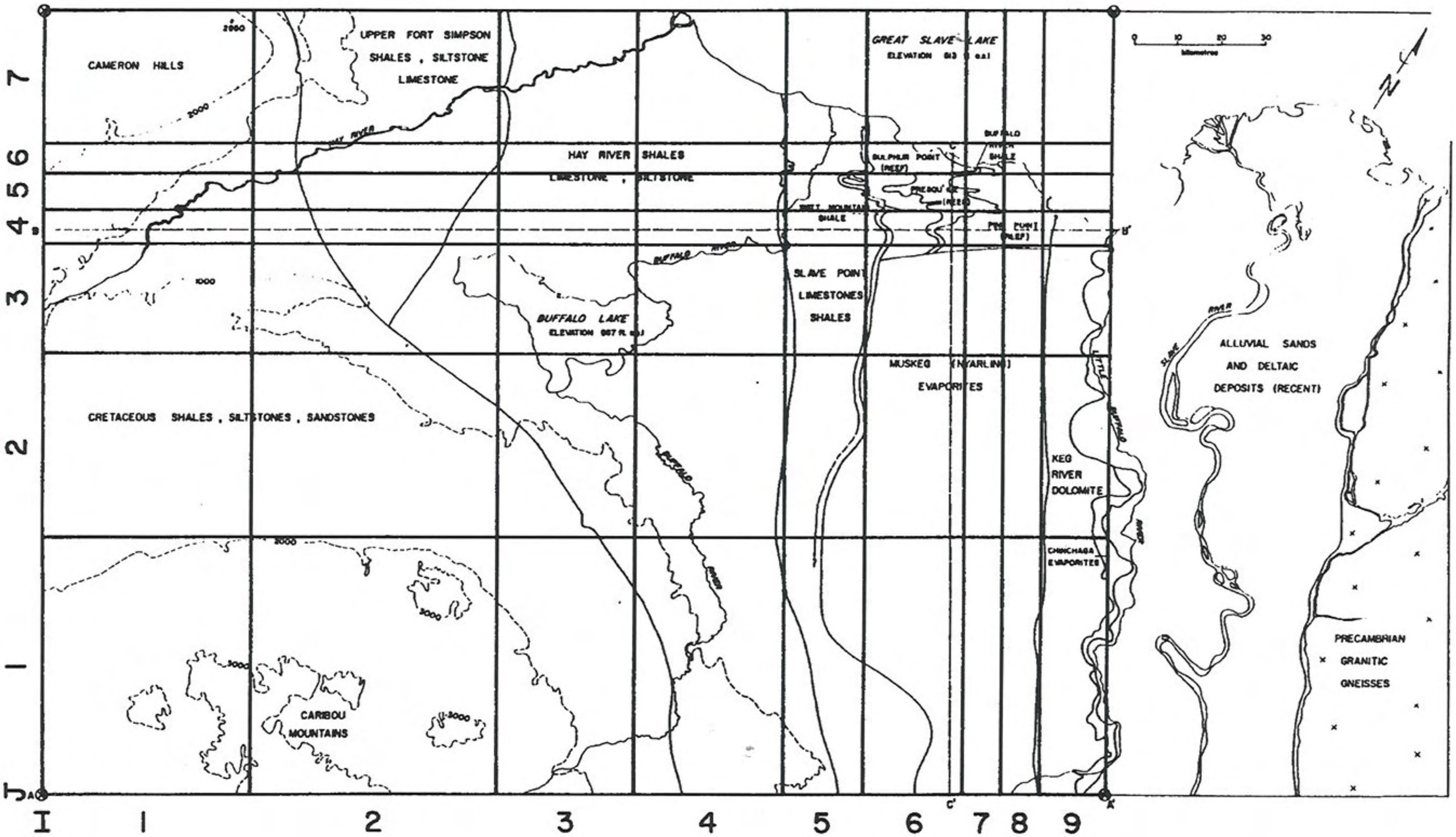


Figure 11. Finite-Difference grid used to model the 3-Dimensional ground water system in the Pine Point area

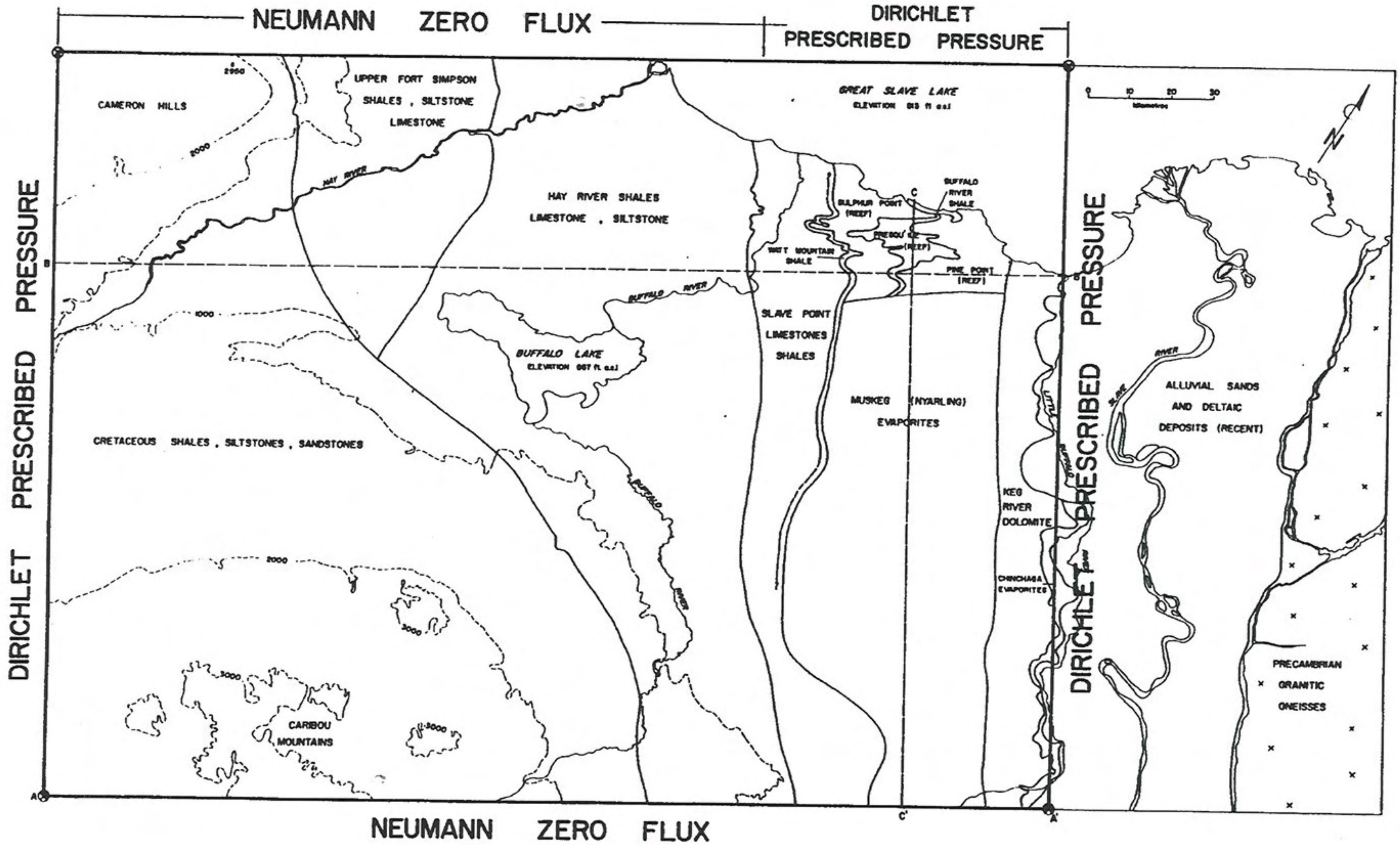


Figure 13. Boundary conditions utilized in the 3-Dimensional model of the response of the ground water system to mine dewatering

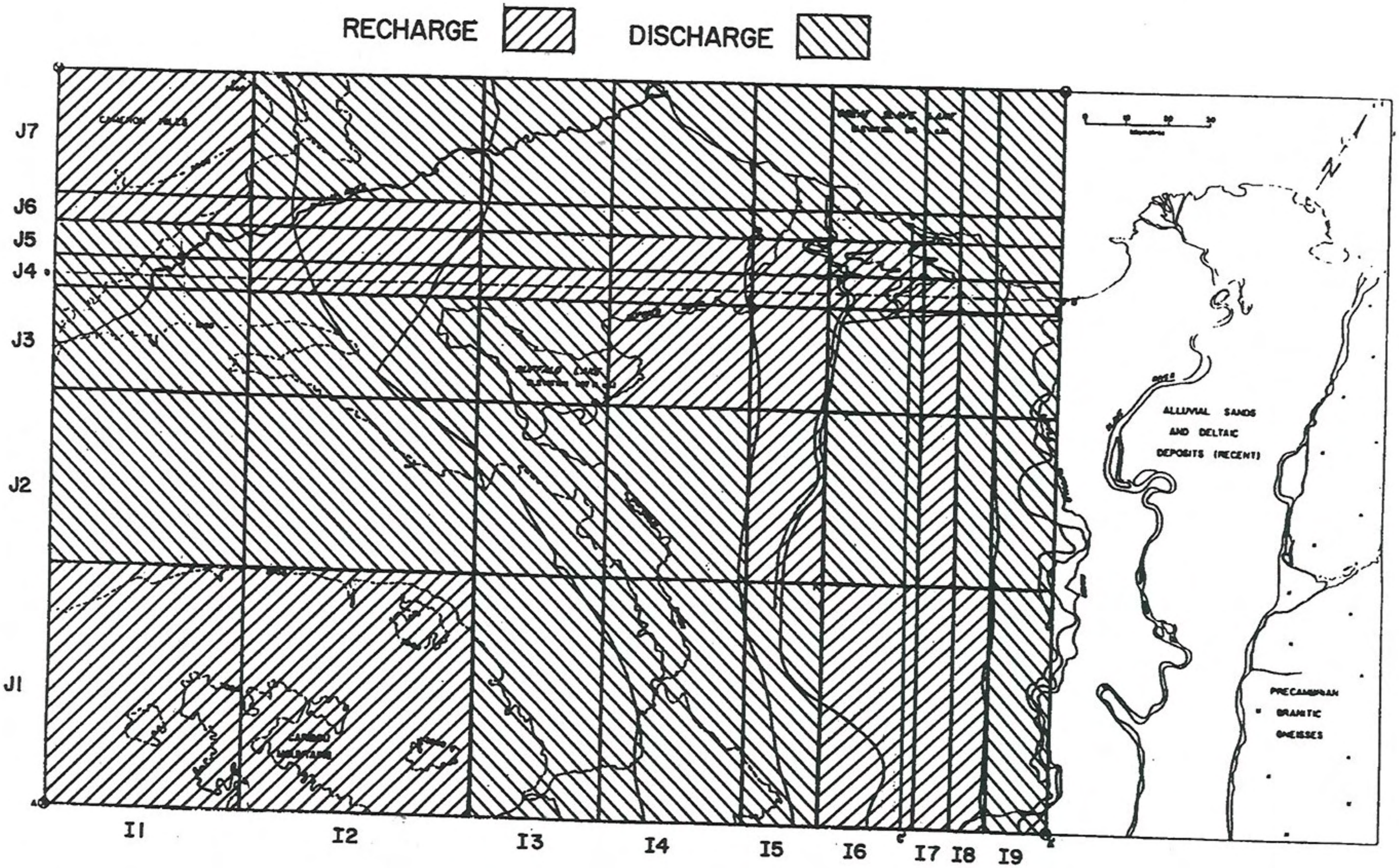


Figure 14. Distribution of recharge and discharge ("subfiltration" - see text) from steady-state calibration

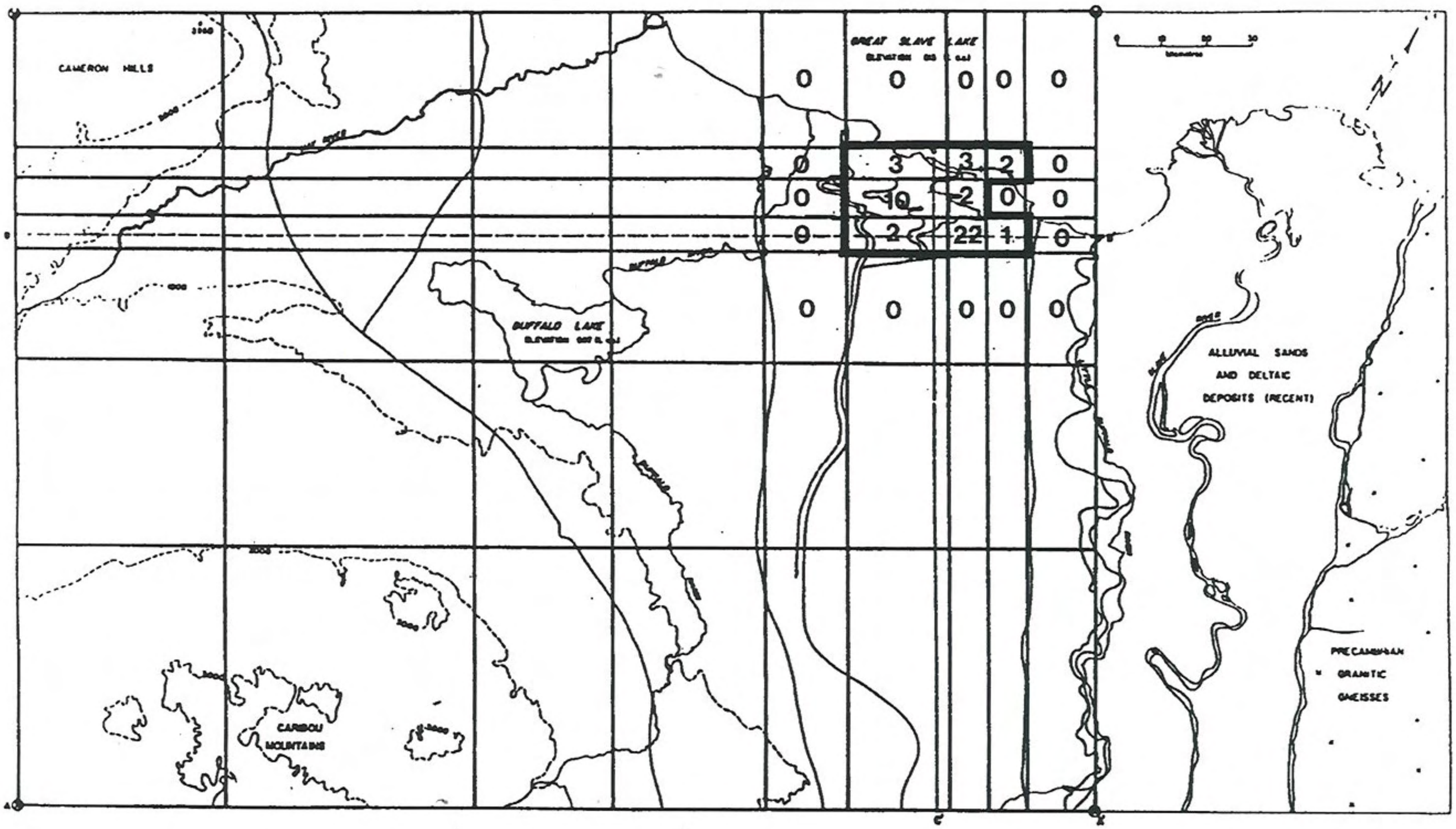


Figure 15. Water table drawdown, 1978. Heavy line represents approximate extent of 1 metre drawdown

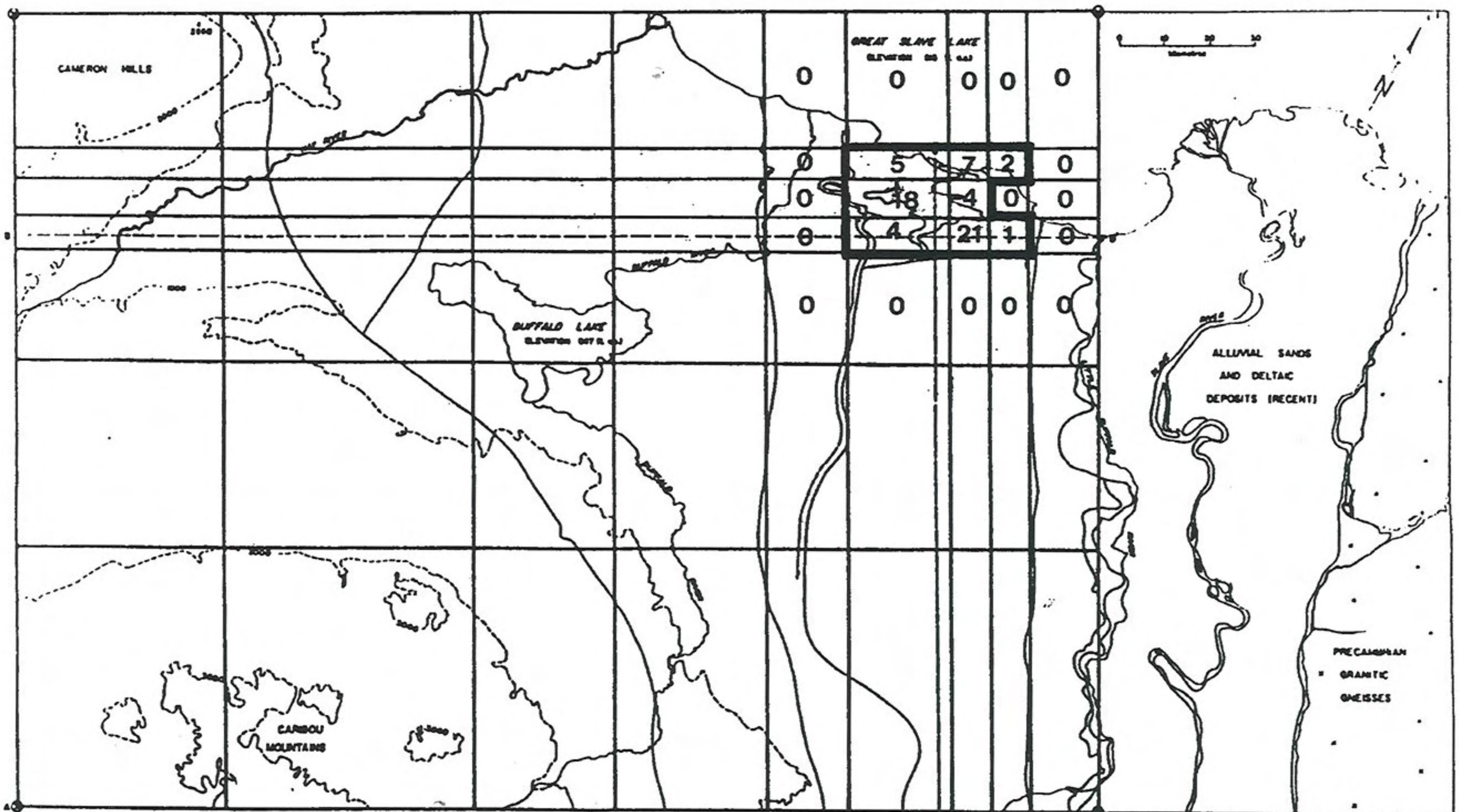


Figure 16. Water table drawdown, 1982. Heavy line represents approximate extent of 1 metre drawdown

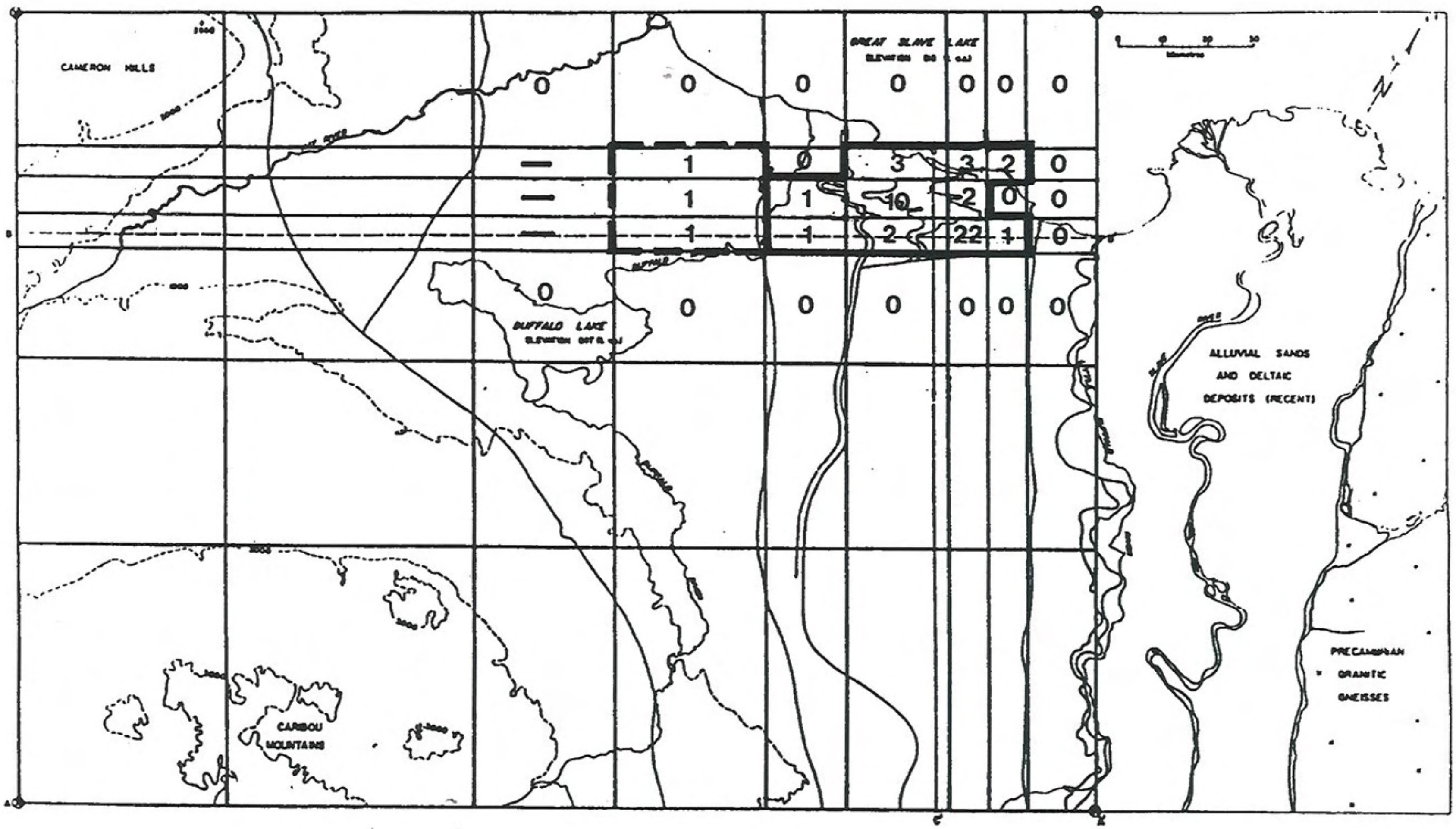


Figure 17. Drawdown in the Pine Point Barrier Reef Complex, 1978. Heavy solid line indicates approximate extent of 1 metre drawdown. Heavy dashed line results from uncertainty due to coarse grid discretization

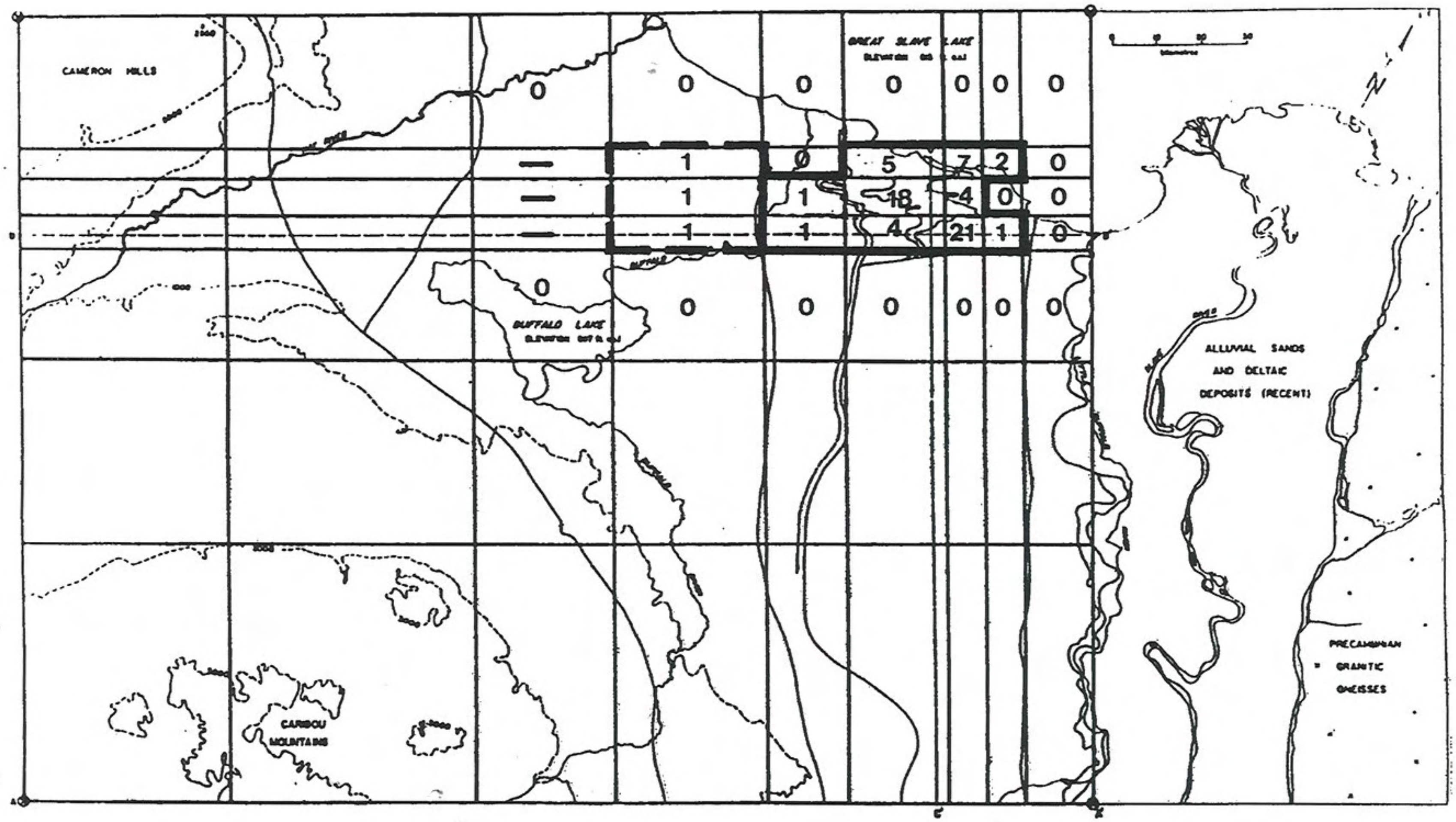
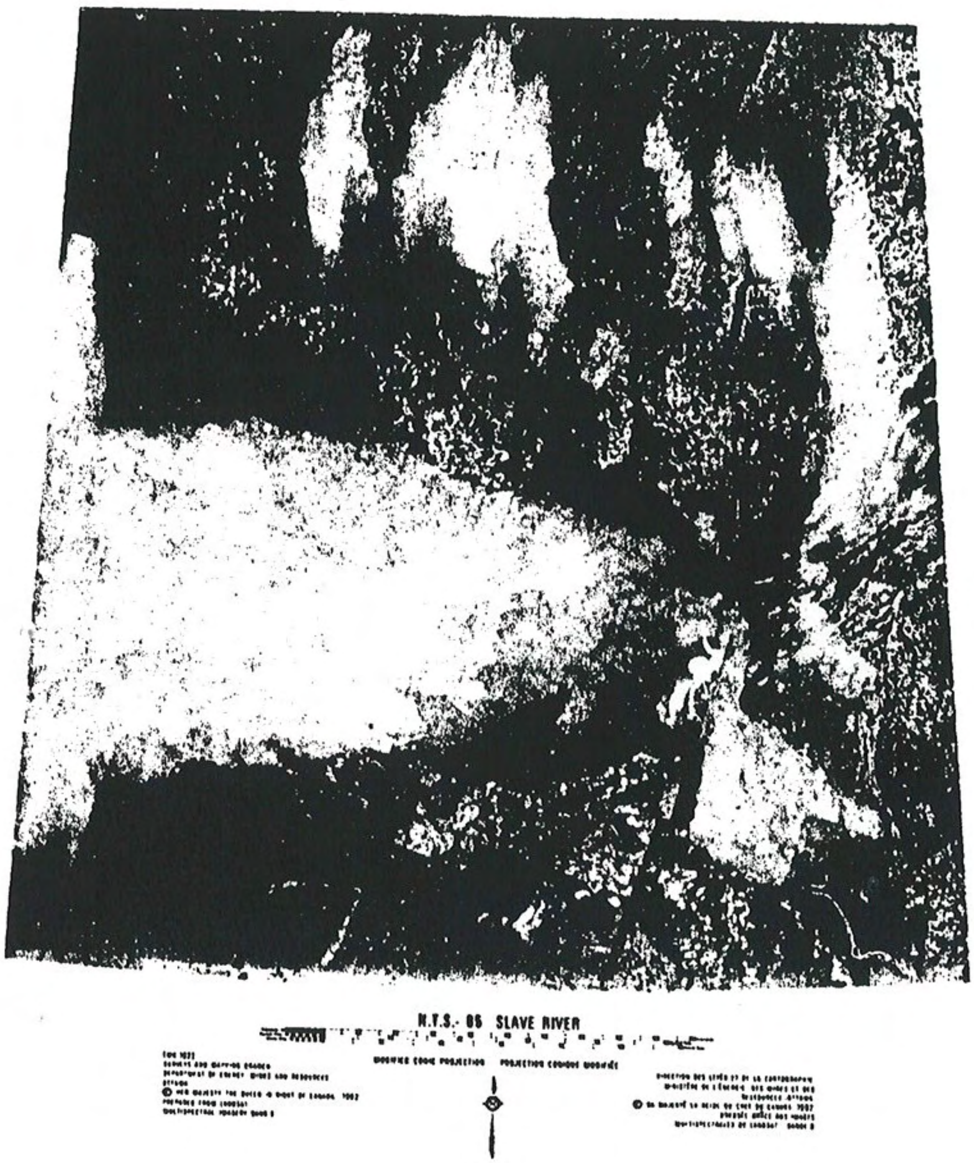
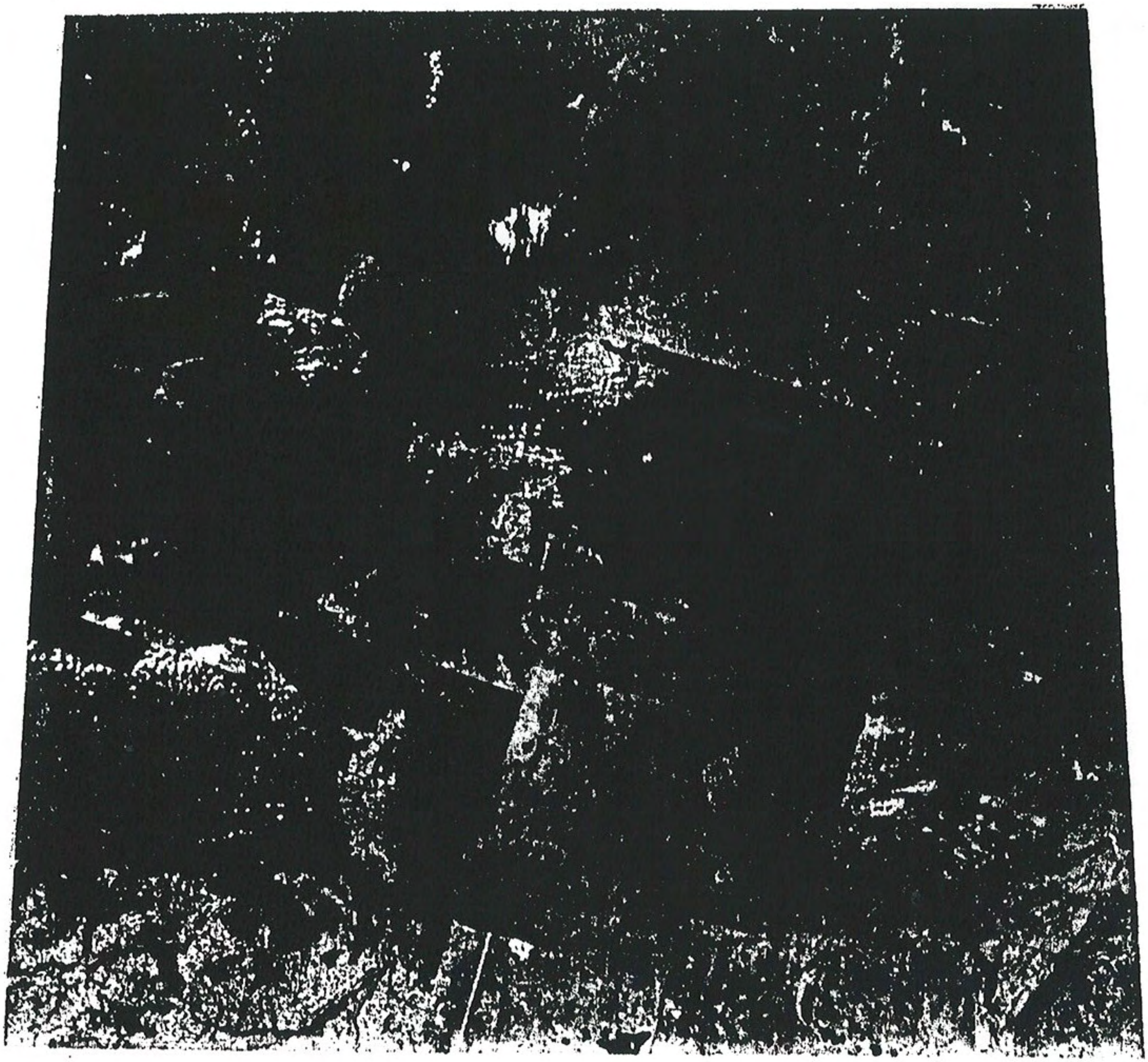


Figure 18. Drawdown in the Pine Point Barrier Reef Complex, 1982. Heavy solid line indicates approximate extent of 1 metre drawdown. Heavy dashed line results from uncertainty due to coarse grid discretization

APPENDIX I

APPENDIX II


N.T.S.- 85 SLAVE RIVER



HAY RIVER