

Pumping at Pine Point Mines [m^3/day]¹⁾

1980	Jan.	March 5	Apr. 12	May 15	June 10	June 30	Aug. 11	Sept. 9	Oct. 12	Nov. 5	Nov. 29	Dec. 29
South trend												
S-65	12,221	6,532	12,297	13,066	27,240	26,737	28,182	27,318	28,394	0		
R-61	37,007	37,587	38,124	45,091	53,859	53,154	54,145	52,797	56,407	0		
T-58												
W-17												
X-15												
Sub-total	49,228	44,119	50,421	58,157	81,099	79,891	82,327	80,115	84,801	0		
Main trend												
N-81												
K-77												
J-69												
H.2.												
M-64												
K-62												
K-57												
J-44												
O-42												
N-42												
M-40												
Millsite												
Sub-total												
North trend												
A-70	94,084	101,083	102,408	111,713	112,907	107,829	112,203	109,370	110,609	112,304	101,190	92,594
A-55	15,906	17,040	15,895	36,336	41,146	37,126	65,079	78,638	83,161	83,177	85,592	84,301
Sub-total	109,990	118,123	118,303	148,109	154,053	144,955	177,282	188,008	193,770	195,481	186,782	176,895
TOTAL	159,218	162,242	168,724	206,266	235,152	224,846	259,609	268,123	278,571	195,481	186,782	176,895

1) 1 USPGM = 5.4432 m^3/day
1 m^3/day = 0.1837 USPGM

Pumping at Pine Point Mines [m^3/day]¹⁾

1981	Feb. 13	Mar 10	Apr. 2	May 12	June 2	June 30	Jul 29	Aug	Oct. 6	Oct. 30	Dec. 2	Jan. '12
South trend												
S-65												
R-61												
T-58												
M-17												
X-15												
Sub-total												
Main trend												
N-81												
K-77							0	12,212	12,212	46,991	53,098	53,166
J-69												
H-2.										0	13,203	13,203
M-64												
K-62												
K-57												
J-44												
O-42												
N-42												
M-40												
Hillsite												
Sub-total							0	12,212	12,212	46,991	66,301	66,369
North trend												
A-70	96,282	82,520	96,018	96,686	100,078	78,938	94,998	75,757	45,864	51,305	(51,305) ²⁾	0
A-55	81,581	81,518	82,578	98,090	93,880	96,530	116,630	131,576	133,471	142,255	142,171	117,532
Sub-total	177,863	164,038	178,596	194,776	193,958	175,468	211,628	207,333	179,335	193,560	142,171	117,532
TOTAL	177,863	164,038	178,596	194,776	193,958	175,468	211,628	219,545	191,547	240,551	208,472	183,901

1) 1 USGPM = 5.4432 m^3/day
 1 m^3/day = 0.1837 USGPM

2) On November 1 and 2 only

Pumping at Pine Point Mines [m³/day]

1982	Feb. 2	Feb. 26	Apr. 1	May 7	June 10	Jul 9	Aug. 13	Sept. 3	Sept. 27	Oct. 29	Dec. 10	Jan. 4
South trend												
S-65												
R-61												
T-58												
W-17												
X-15												
Sub-total												
Main trend												
N-81												
K-77	70,431	74,075	89,017	103,272	99,021	0			0	25,957	25,914	0
J-69												
H.Z.												
M-64	28,437	26,727	29,004	37,981	37,981	38,394	38,622	38,622	44,548	44,548	0	
K-62												
K-57												
J-44												
O-42												
N-42												
M-40												
Millsite												
Sub-total	98,868	100,802	118,021	141,254	137,002	38,394	38,622	38,622	44,548	70,505	25,914	0
North trend												
A-70												
A-55	115,050	122,976	133,064	129,054	126,726	112,802	116,029	126,565	132,022	133,349	132,214	129,039
Sub-total	115,050	122,976	133,064	129,054	126,726	112,802	116,029	126,565	132,022	133,349	132,214	129,039
TOTAL	213,918	223,778	251,085	270,307	263,728	151,196	154,651	165,187	176,570	203,854	158,128	129,039

1) 1 USGPM = 5.4432 m³/day1 m³/day = 0.1837 USPGM

Pumping at Pine Point Mines [m^3/day]¹⁾

1983	Jan	Feb	Mar	Apr	May	June 30	Aug. 12	Sept. 18	Oct. 4	Nov. 8	Dec. 8	Jan. 5/11
South trend												
S-65												
R-61												
T-58												
M-17												
X-15												
Sub-total												
Main trend												
N-81					0	72,659	87,000	79,800	122,960	97,780	104,320	100,300
K-77												
J-69												
H.Z.												
M-64												
K-62												
K-57												
J-44												
O-42												
N-42												
M-40												
Millsite												
Sub-total					0	72,659	87,000	79,800	122,960	97,780	104,380	100,300
North trend												
A-70												
A-55	116,200	118,200	111,900	121,000	144,904	144,904	141,900	135,400	134,730	141,440	156,600	172,000
Sub-total	116,200	118,200	111,900	121,000	144,904	144,904	141,900	135,400	134,730	141,440	156,600	172,000
TOTAL	116,200	118,200	111,900	121,000	144,904	217,563	228,900	215,200	257,690	239,220	260,980	272,300

1) 1 USGPM = 5.4432 m^3/day
1 m^3/day = 0.1836 USGPM

2) 1984

Comparison of Tine Point ^(Kans 7) dewatering area
to Severoulsk ^{Kans 7} dewatering area
in the USSR.

No. mines: 5 in 3 clusters (2 = 2)
type underground:

climate: precipitation: 480 mm
lowest temperature: -5°C with winter T of 5°C
mining covered methods 1933

1. for open cut
2. underground mine workings with inclined shaft
3. underground mine workings with vertical shaft

mining depth 200 m
elevated

geology Shegultanien. Syncline with
sedimentary and volcanic
rocks
karstic limestone up to 100 m
thick
numerous embankments in coastal
deposits (25-30 per km²)

Same of groundwater
release from ~~precip~~

- a. ^{release from} precipitation absorbed by numerous
karst features
- b. infiltration of surface waters in
river channels
- c. ground water flows from the non-
karst areas surrounding the karst basin

protection against flooding

- a. extensive drainage systems (pumping)
- b. lining of riverbeds with concrete

extent of disturbance of the natural regime
of ground and surface waters $> 2200 \text{ km}^2$

permeability 10^{-2} to 10^{-5} at greater depth

drawdown 1977 about 300 m extend
linear 38 km with relaying rivers
at both ends (Fig 1)

drawdown actual 1977 300 m
limestone dissolved $200,000 \text{ m}^3$
other substances $30,000 \text{ m}^3$
void space increased by 0.001%

R-190 kA

a) high permeability because of
fracturing!

b) flow direction by Vogel with
arbitrary

c) X-25 was static water level
was 656.05
while it was 603.12 at the pump well

d) produced flow
because water level was higher
than level in bedrock

SEVEROKH RALSK, Ural, USSR

Pia

1. mining information

- Saevite mining
- underground mine workings
- mining commenced 1933
- dewatering commenced about 1945
- methods: - pumping
- lining of rivers with concrete
- groundwater flow through mining area before mining about $1 \text{ m}^3/\text{sec}$

active

g. mining area elongated about 30 km long

h. permeability measured $10^{-3} - 10^{-5} \text{ m/sec}$

i. Transmissivities determined by mathematical model

16 - 412

43 - 2648

- upper aquifer (near mine) 1.9×10^{-4} to $4.8 \times 10^{-3} \text{ m}^2/\text{sec}$
- lower aquifer (east of mine) 5×10^{-4} to $3.1 \times 10^{-2} \text{ m}^2/\text{sec}$

j. ~~Sanction~~ - max drawdown allowed 20 m

k. linear extension of affected area 36 km between two adjoining rivers

l. extend of disturbance of the natural regime of ground and surface waters: $> 2200 \text{ km}^2$

m. For the period of 30 years period of mine drainage ground waters base approximately dissolved about

limestone 200 000 m^3 ~~etc~~

300 000 m^3

void space increased by 0.001 %

1. mining

a. C

b. 0

c. 1

d. 1

e. 1

f. 1

g. 1

h. 1

i. 1

j. 1

k. 1

l. 1

m. 1

Pine Point, NW, Canada

1968 - 1973

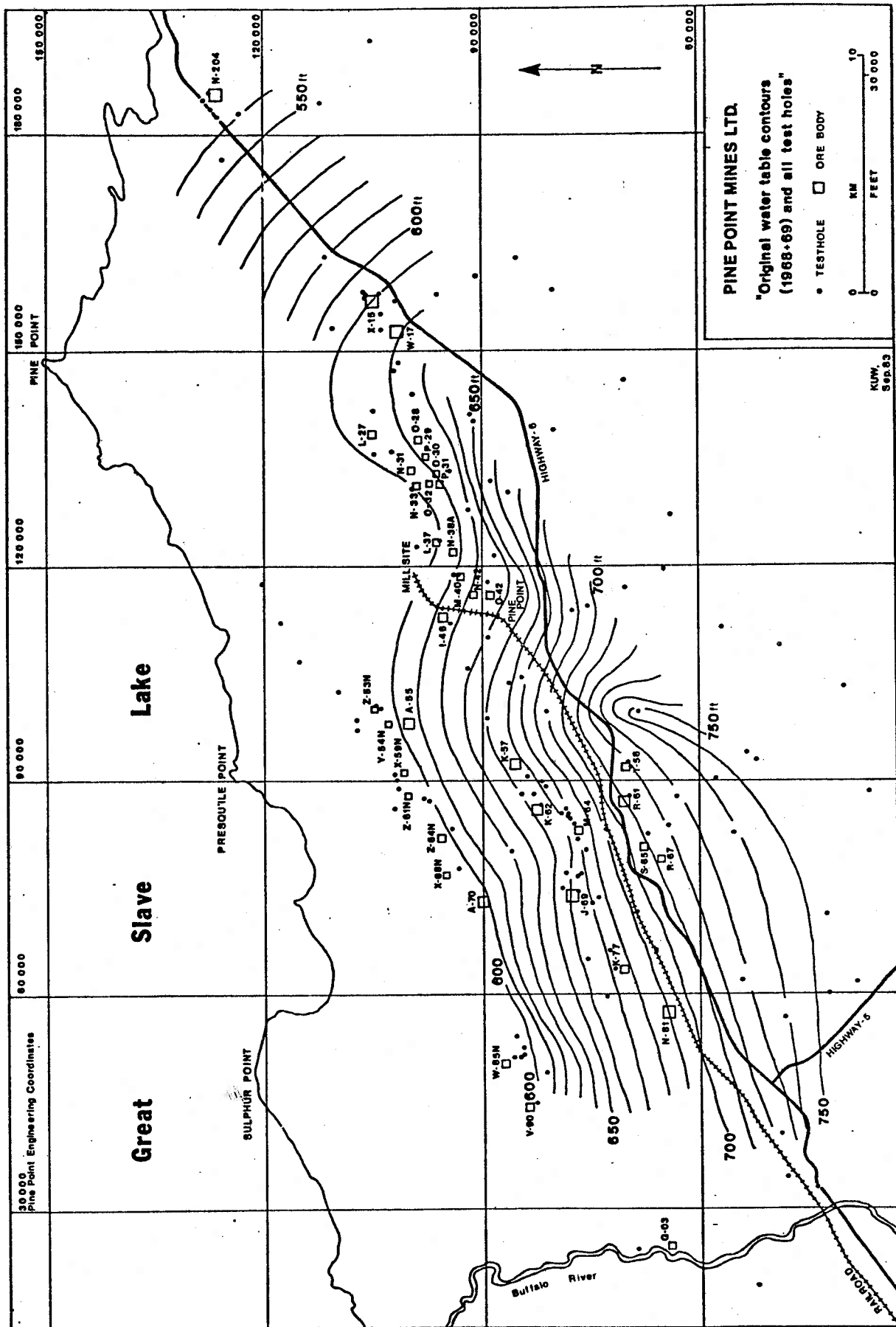
Summary information

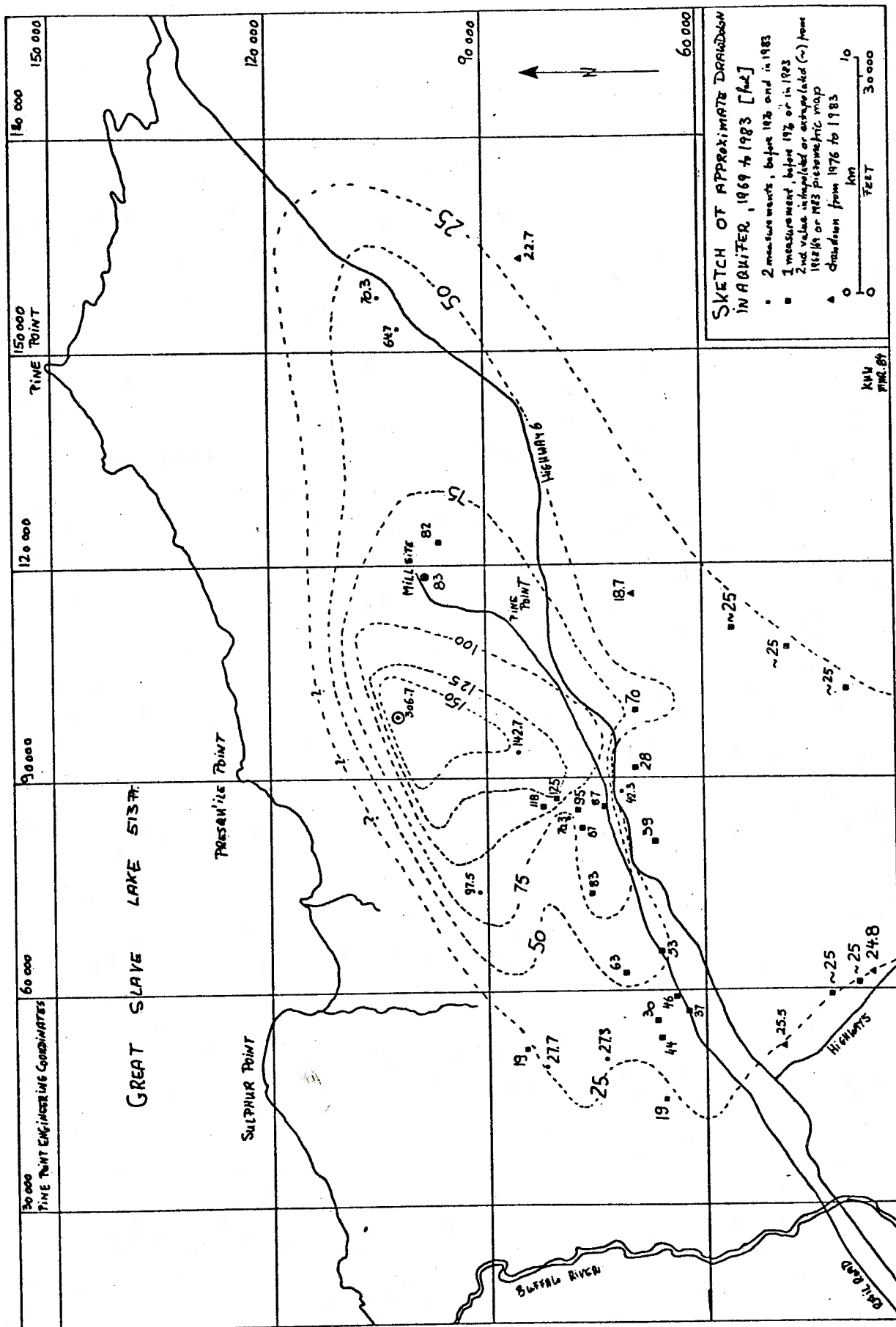
- a. Lead zinc mining
- b. open pit mining
- c. mining commenced 1965
- d. dewatering commenced 1968
- e. methods pumping
- f. groundwater flow through mining area before mining about $1 \text{ m}^3/\text{sec}$
- g. mining area elevated about 30 km long
- h. $\alpha = 7$ permeability measured $10^{-2} - 5 \times 10^{-5} \text{ m/sec}$ $3 \cdot 2 \cdot 5 \cdot 7 \times 10^{-2}$
 - i. Transmissivities determined by pump tests
 - Pine Point mines 5.0×10^{-3} to $2.0 \times 10^{-2} \text{ m}^2/\text{s}$
 - Western mines
 - Consultant 1 : 2.4×10^{-3} to $1.7 \times 10^{-1} \text{ m}^2/\text{s}$
 - Consultant 2 : $3.5 \times 10^{-2} \text{ m}^2/\text{s}$
 - j. max drawdown observed : about 120 m
 - k. disrupted may be 45 km
- l. extent of disturbance of the natural regime of ground and surface waters : disrupted may be between 3000 - 5000 m²
- m. For the 15 years period of mine drainage groundwaters have approximately disturbed

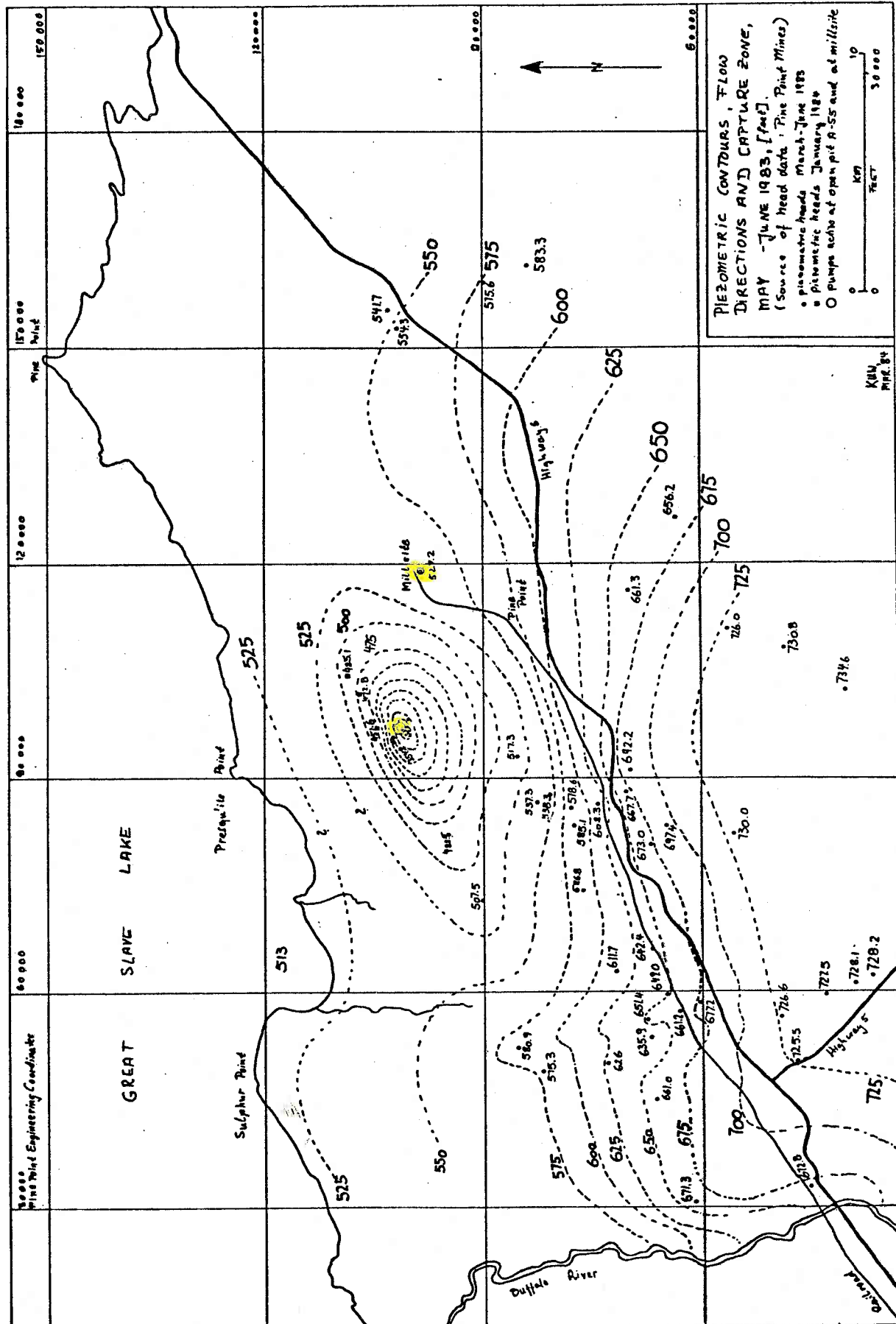
limestone :

gypsum :

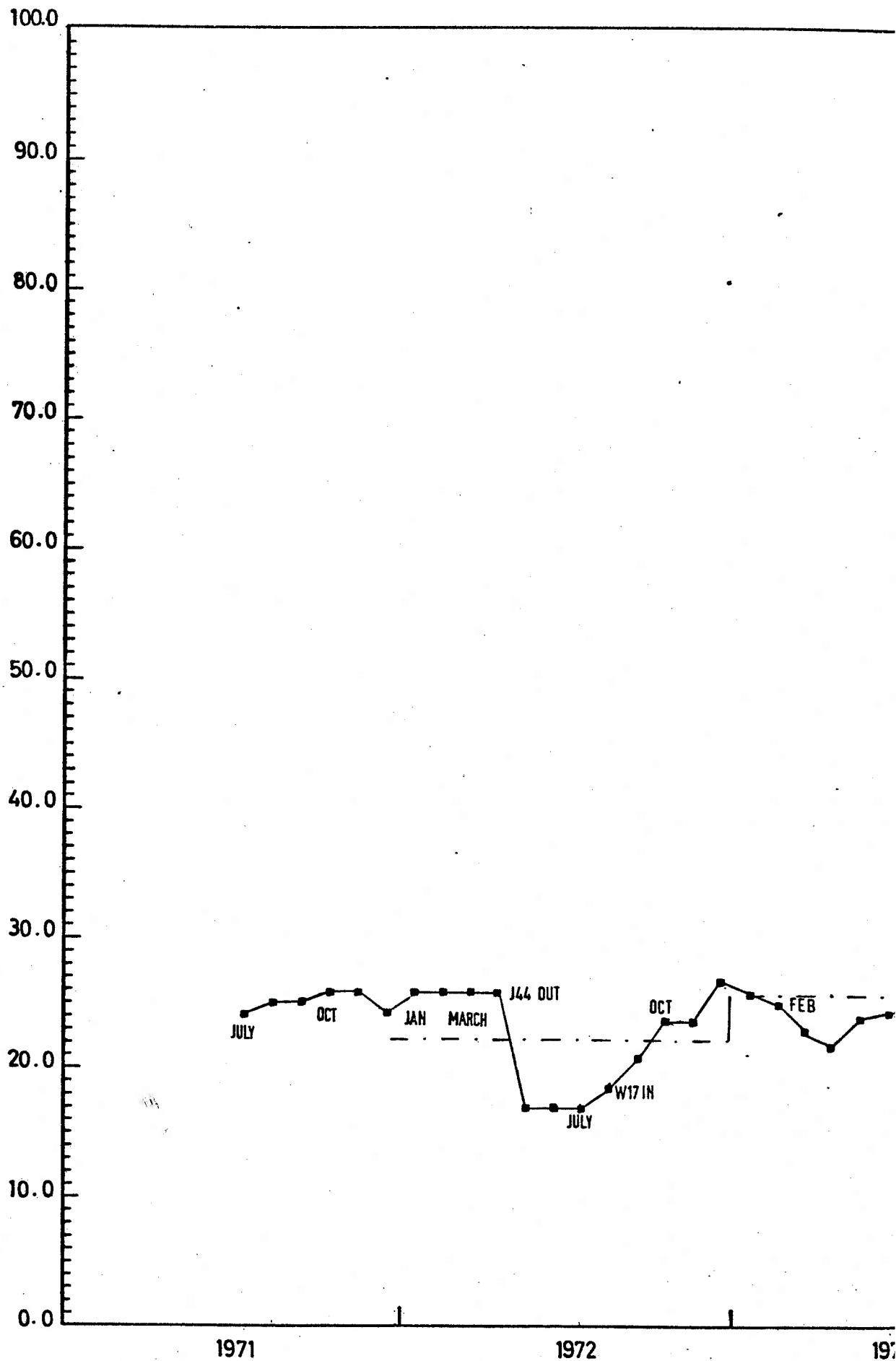
silt :

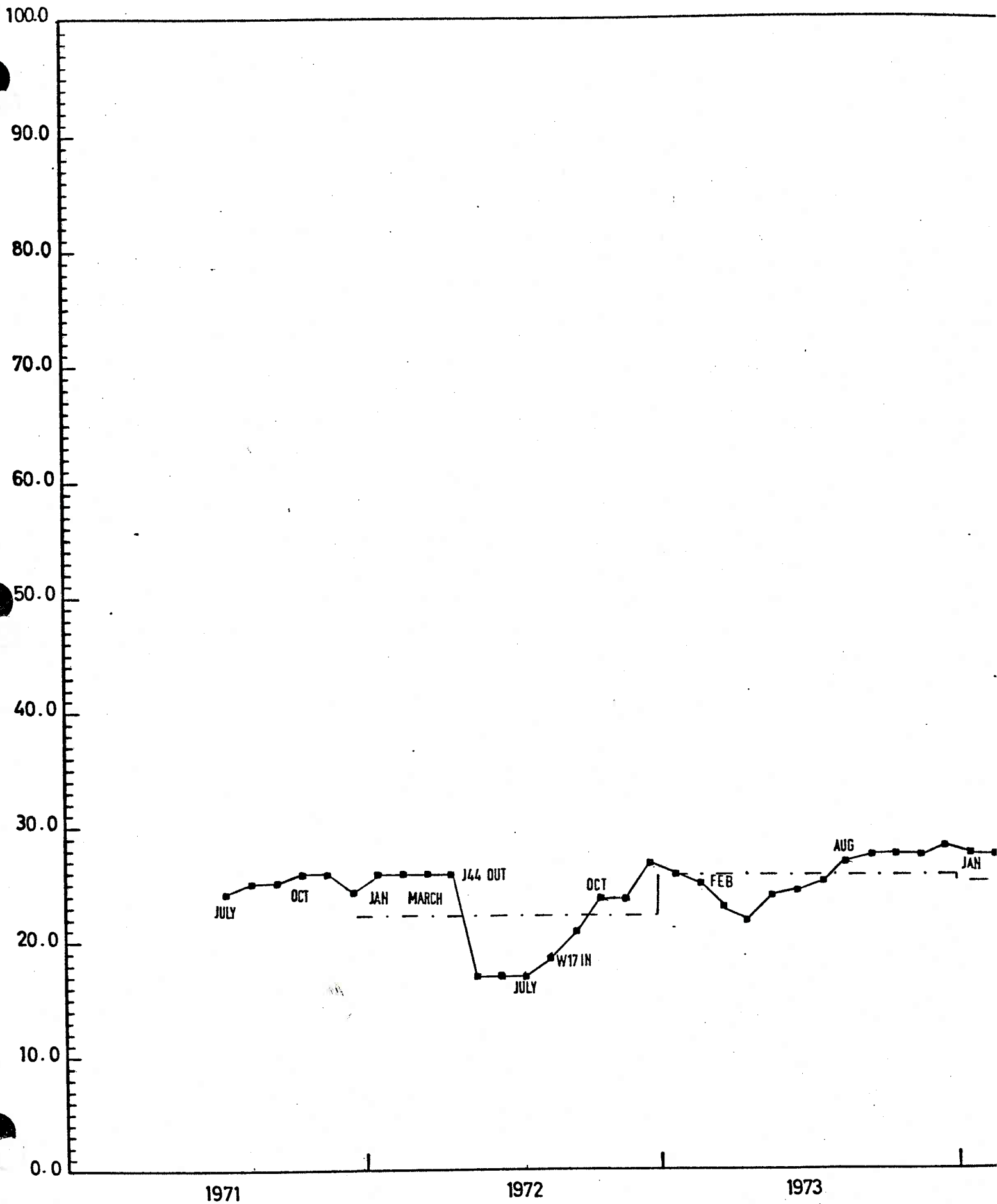


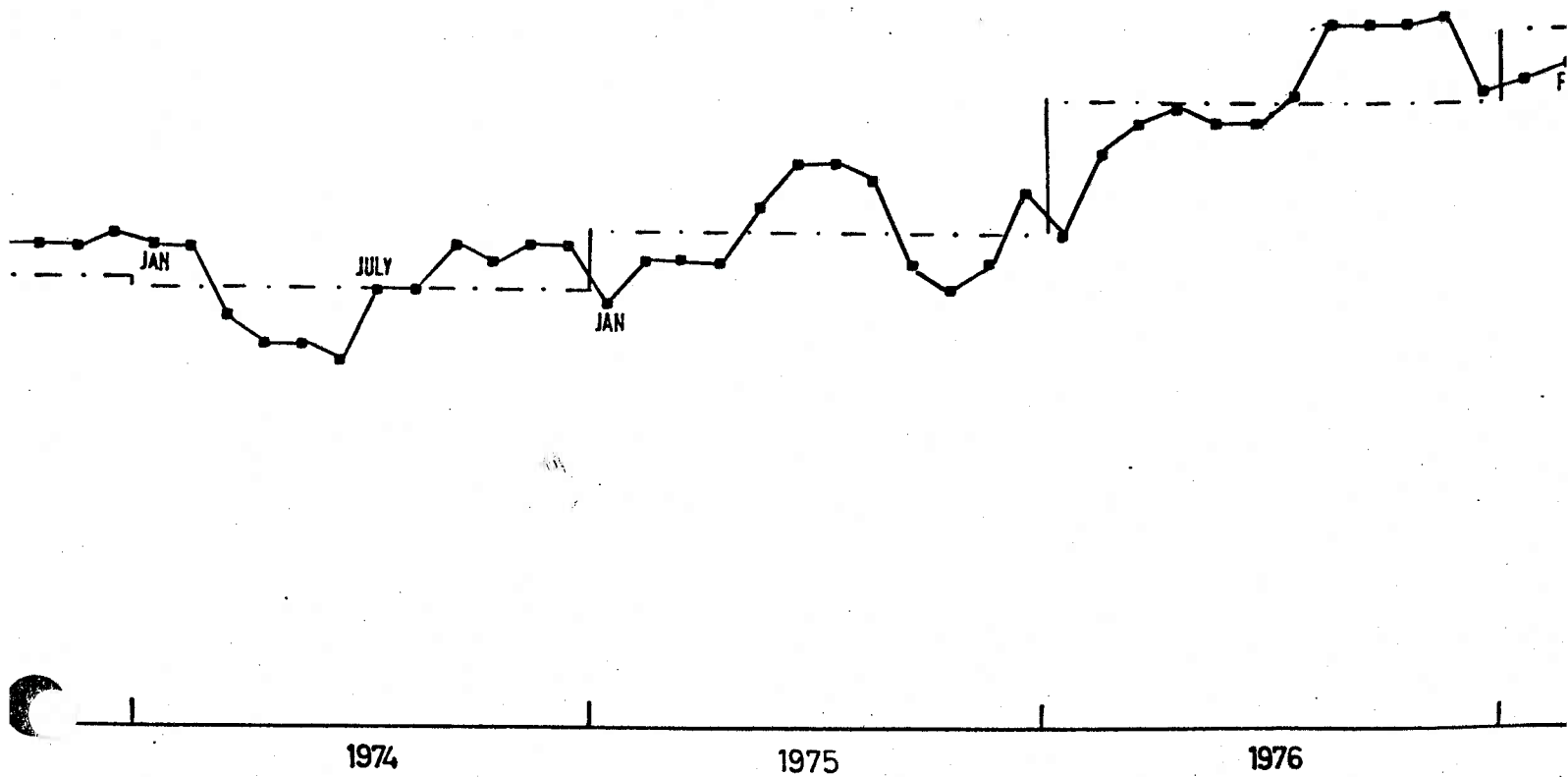


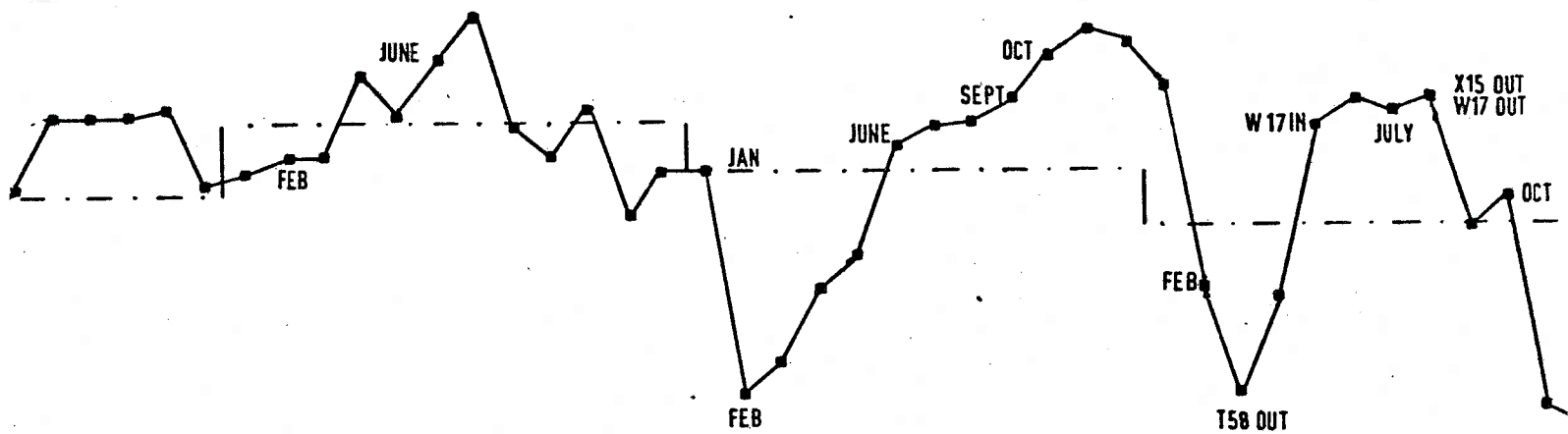


AVERAGE DISCHARGE 1000*USG/MINUTE









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IT

OCT

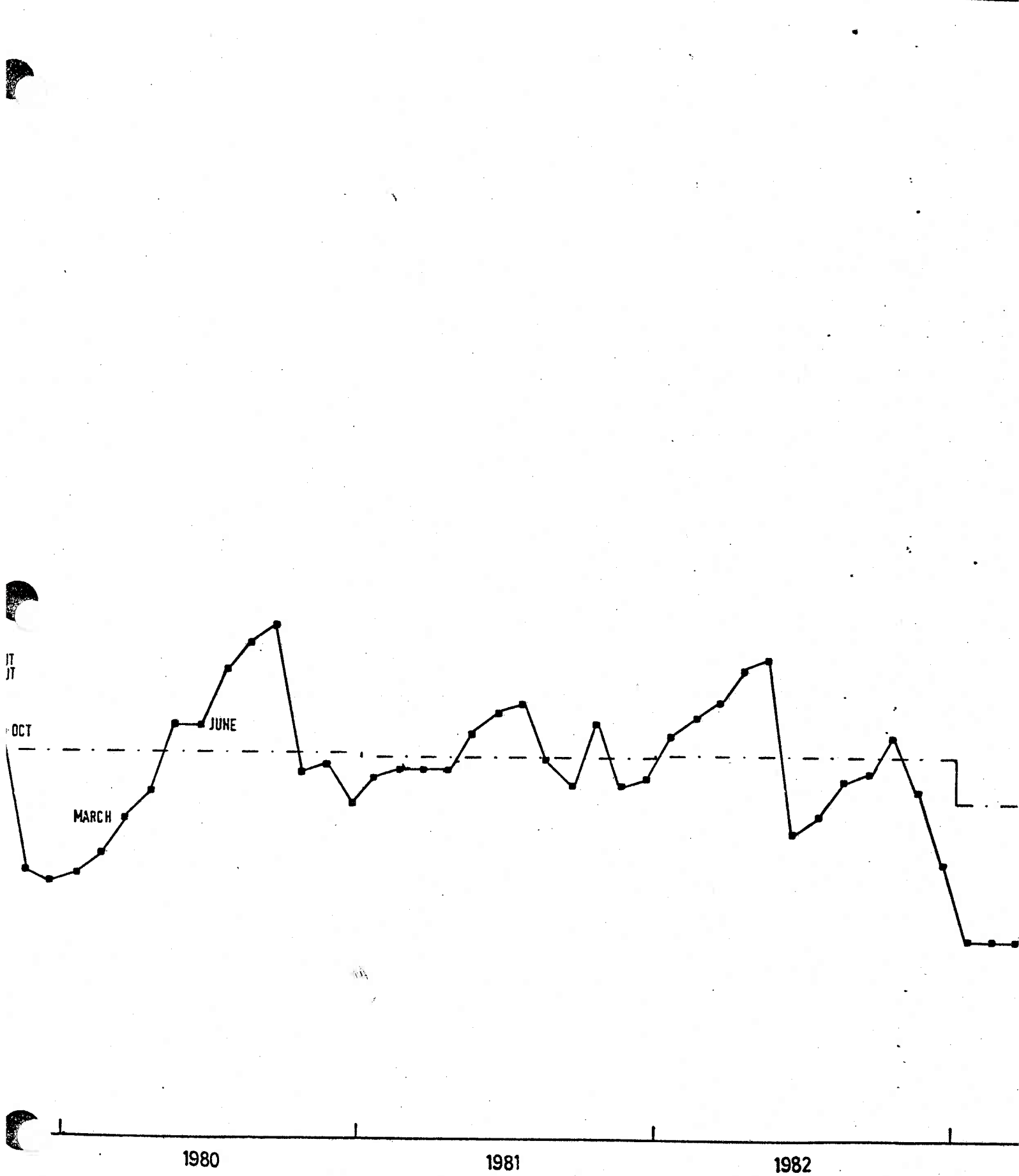
MARCH

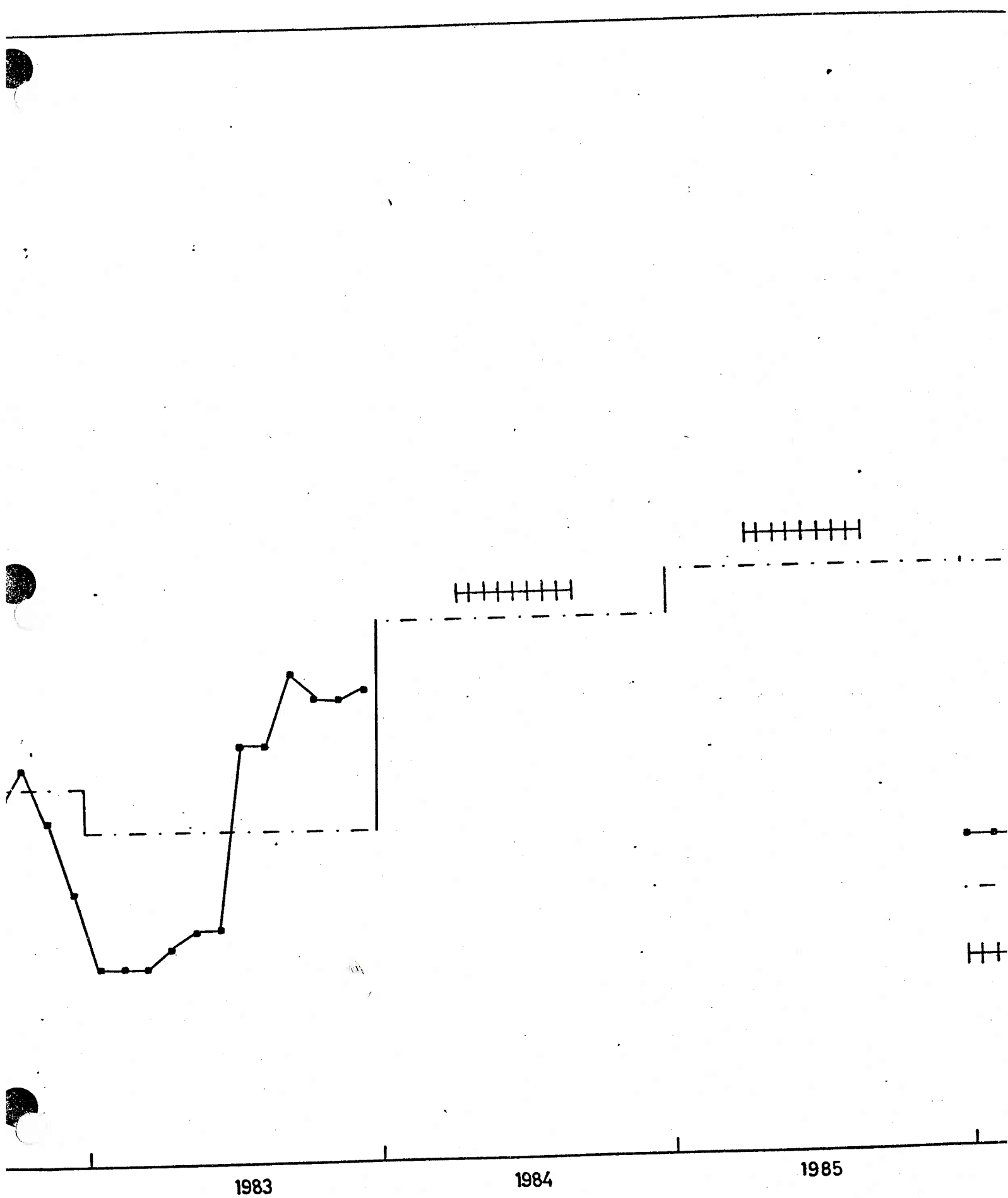
JUNE

1980

1981

1982





Department of Indian &
Northern Affairs
Northern Operations Branch

AUG 14 1984

WATER MANAGEMENT
YELLOWKNIFE, N.W.T.

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MONTHLY DISCHARGE

TOTAL ANNUAL DISCHARGE

MAXIMUM DAILY DISCHARGE

1000 USG/MIN

m³/sec

1986

1987

1988

6.0

90.0

80.0

5.0

70.0

60.0

4.0

50.0

3.0

40.0

30.0

2.0

20.0

1.0

10.0

5. GROUNDWATER FLOW NEAR OREBODIES IN THE PINE POINT DISTRICT

BACKGROUND

Figure 5-1 shows the location of selected pits discussed in this chapter. The regional spread of orebodies known to us is shown in Figure 3-50.

FIGURE 5-1

Permeabilities and transmissivities determined near orebodies were reported in the previous chapter (Table 4.4). Transmissivities range from 0.005 to $0.172 \text{ m}^2/\text{s}$ based on the assumptions inherent in the application of pump-test theory to karstic systems. Dewatering requirements for the orebody R-190, for a transmissivity of $0.172 \text{ m}^2/\text{s}$, were determined to be 310 000 US gpm or about $19.5 \text{ m}^3/\text{s}$ (Golder, 1980). This enormous rate of flow gives an impression of the magnitude of groundwater flow which can occur in a limited area. Pump testing at R-190 caused drawdown at the orebody X-25 at a distance of 4270 m within four hours (A. Randall, personal communication, 1982). The drawdown observed at X-25 was greater than the one observed in the observation holes surrounding the R-190 pump test (A. Randall, personal communication, 1982). Observation holes at X-25 had been equipped with water-level monitors previous to this pump test. Water levels at X-25 were found to respond readily to changes in the Pine Point dewatering activity (S. Hoffman, personal communication, 1982) which at the time, was taking place 20 to 25 km to the east. These observations confirm that high permeable zones connect orebodies along the trend of the hinge lines, following the strike of the Presqu'ile facies (compare Figs. 3-16 and 4-6).

Of prime interest for the regional groundwater flow pattern and for the dewatering at open pits is the answer to the question whether groundwater 'wells up' from greater depth in the area of the extremely permeable Pine Point Barrier and specifically near the orebodies. Geological

indications for the existence of effective karstic connections at greater depth have been described in Chapter 3. Hydrodynamic indications were presented by Golder Associates (1980), who described the existence of a groundwater ridge or mound for the area of the R-190 orebody (see Fig. 5-2) which they tentatively related to regional tectonics and upwelling of deep groundwater flow. Water samples

FIGURE 5-2

collected from the pumped well showed a salt content of 103 mg/l Cl^- and 1720 mg SO_4^{2-} (sample WEY 436), indicating some inflow of deeper saline groundwater during the pump test.

HYDROCHEMICAL OBSERVATIONS AT OREBODIES

BACKGROUND

In Chapter 3, orebodies were characterized as (1) 'normal, interconnected tabular and prismatic' (2) 'isolated prismatic' and (3) 'anomalous' prismatic. We collected hydrochemical data from dewatering pumps for type (1) at pits A-70, J-69, K-77, M-40 and R-190; for type (2) at R-61, S-65 and T-58 and for type (3) at A-55, W-17 and X-15. In addition information on some hydrochemical aspects has been provided by Santos (1975) for the orebodies K-57 (type 1) and W-17 (type 3). Santos (1975) concentrated on the Zn and Fe contents of the pumped water. Our study concentrated on the major-ion content of the pumped water to distinguish different groundwater flow systems identified by 'major-ion' contents. Appreciable amounts of salt water were detected at the orebodies A-55, A-70 and W-17.

NORMAL INTERCONNECTED TABULAR AND PRISMATIC OREBODIES

From our point of view the most interesting example of this group of orebodies is the orebody A-70, because it shows a locally pronounced discharge of salt water and because artesian conditions existed there before dewatering commenced. Figures 5-3 and 5-4 show the distribution of the Cl^- and SO_4^{2-} values, respectively for the area of A-70.

The previous contour plots and three-dimensional plots of the same properties (Figs. 5-5 and 5-6) indicate the existence of a zone of upwelling groundwater close to the orebody A-70. This zone may have a direction similar to that of the trend of the Prebble and McDonald Faults (about 45°E).

FIGURE 5-3

FIGURE 5-4

FIGURE 5-5

FIGURE 5-6

Interpretation of the data also would allow the postulation of the existence of a NS structure element in the area. From the above data two conclusions can be drawn: (1) in the area of the hingeline in the north trend, and probably also in the main and south trends, permeability systems reach into greater depth and (2) from a hydrogeologic point of view, 'normal' tabular karst systems may not be much different from the 'anomalous' unconsolidated karst systems, as both transmit deeper saline groundwater, at least in some areas.

FIGURE 5-7

At the orebody K-57, Santos (1975, p.7) concluded that the Zn + Fe contents in the pumped water followed "two distinct trends, or preferred routes, the principal one through W.H. 6 and W.H. 7 (N.W. Trend) and an almost N-S trend from W. H. 9 and W. H. 7 as indicated by the adjusted Zn + Fe contours on Plate 6" [of Santos 1975; compare Fig. 5-7 of this report]. An occurrence of Pb in the water was not detected. These chemical data suggested to Santos (1975) that there exist tectonical NW-SE and N-S zones at the K-57 orebody exerting an important hydrogeological influence. Both directions "correlate fairly well" with structural trends found in the area (Santos, 1975, p. 7).

ISOLATED PRISMATIC OREBODIES

The orebodies R-61, S-65 and T-58 belong in this group of orebodies that did not conform to the initial exploration and ore genesis concepts adopted by the Northern Lead Company and its successor, Pine Point Mines. R-61 and S-65 were discovered by Coronet Mining as the C-1 and C-3 anomalies, respectively, during an induced polarization survey.

Of course these orebodies are not isolated from karstic systems and groundwater flow as their name might suggest. Groundwater flow patterns in the area were actually such that dewatering at R-61 significantly affected the water levels at S-65, but not at the much nearer orebody T-58. In general, total groundwater flow towards the R-61 orebody was much larger than expected from a pump test. Half of the pumps were installed in the SW corner of the pit within a high permeable zone extending from the S or SW. The evaluation of SO_4^{2-} data indicates the existence of a hydrochemical trend pointing into the same corner, either from the N or the NE (see Fig. 5-8). No structural conclusions can be drawn from the chloride data. Figure 5-9 shows background data below 30 mg/l chloride contents.

FIGURE 5-8

FIGURE 5-9

Some further aspects of the hydrochemistry of the orebody S-65 are discussed below in context with bio-chemical considerations.

ANOMALOUS PRISMATIC OREBODIES

These orebodies are associated with unconsolidated breccia chimneys reaching far down into the Chinchaga Formation or, possibly, deeper. Some of the largest orebodies (e.g. A-55, W-17 and X-15) are associated with these suspected hydrodynamic-blowout structures (compare Chapter 3). Again, these orebodies did not conform to the initial exploration and ore-genesis concepts of Pine Point Mines and its predecessor, the

Northern Lead Company. They were discovered by Conwest (Anomaly 408; orebody A-55) and Pyramid Mining (Anomaly 1 and 2; orebodies X-15 and W-17). The pit X-15 was largely dewatered by the pumping at the neighboring open pit W-17. We will discuss the hydrochemistry of the orebodies W-17 and A-55 in detail.

Santos (1975, overlay to Plate 12) showed the position of the orebody W-17 in the pit and a seemingly related approximately SE-NW trending series of three collapse structures (Fig. 5-10). He identified a zone of comparatively high Zn + Fe values with this trend (Fig. 5-11). A zone of comparatively high combined concentrations also was found near the NE corner of the pit (Well hole 12). Santos (1975, p. 8) concluded that "three trends are apparent, a NW trend, a NS trend and on almost EW trend".

 FIGURE 5-10
 FIGURE 5-11
 FIGURE 5-12
 FIGURE 5-13
 FIGURE 5-14

In 1977, 1978 and 1979 we collected water samples from the W-17 pit-dewatering system (location of wells shown in Fig. 5-10). Figures 5-12 and 5-13 show the occurrence of chloride in a contour map and a 3-D representation. Comparing the 3-D representation (Fig. 5-13) with Figure 5-14 (showing the depth of the pumping wells and their position in the pit environment) and with Figure 5-10 several conclusions can be drawn: (1) salt water is drawn up through the orebody itself (pumps 31, 33 and 34); (2) salt water also occurs at the perimeter (pumps 13, 14, 17 and 18) indicating either a flow direction from the central core (unconsolidated collapse) to the NE towards orebody X-25, or the existence of an additional deep reaching collapse in the area; (3) the salt water is drawn up from the Chinchaga evaporites or deeper layers; (4) mixing of waters occurs to some degree in the Lower Keg; and (5) Lower Keg Formation and Chinchaga evaporites are important aquifers in the area.

FIGURE 5-15 A,B

FIGURE 5-16 A,B

The sulphate contents of the water, shown in Figure 5-15A and 5-15B and presented in 3-D plots in Figure 5-16A and 5-16B, emphasize the occurrence of high sulphate contents in the salt water. This finding supports our previous conclusion that the high ionic strength of brines and salt water in general causes an increased dissolution of anhydrite and gypsum layers (compare Fig. 3-27 and related discussions in Chapters 3 and 4). The distribution of the SO_4^{2-} values indicates the existence of a SW-NE zone and N-S zone with high sulphate content. Comparison of the 1977 with the 1978 data reveals the sulphate distribution to be stable inspite of strong pumping.

In summary, the hydrochemical results from pit W-17 confirm our conclusions about the vertical extent of karst structures to great depth and about the importance of these pathways for regional cross-formational groundwater flow. In the Pine Point region, finger-printing of groundwater by major-ion chemistry provides the key to an understanding and confirmation of concepts of regional hydrodynamics and karst development.

At the orebody A-55 background values for chloride are between 50 and 60 mg/l. Discharge of salt water, however, is concentrated north of the orebody (Figs. 5-17 and 5-18), near the deeply penetrating breccia chimney of unconsolidated rocks (compare with Figs. 3-38 and 3-39 and associated discussions). The distribution of SO_4^{2-} values (Figs. 5-19 and 5-20) indicate the existance of SW-NE and NW-SE zones of water with higher SO_4^{2-} content.

FIGURE 5-17

FIGURE 5-18

FIGURE 5-19

FIGURE 5-20

STRUCTURAL CONCLUSIONS FROM HYDROCHEMICAL OBSERVATIONS

The occurrence of salt water discharge at 'normal interconnected tabular and prismatic' as well as 'anomalous' prismatic orebodies indicates that karstic system there penetrate to greater depth (Chinchaga Formation or deeper).

The pattern analyses of Cl^- and SO_4^{2-} concentrations of pumped water indicate the presence of the following 'structural' zones: SW-NE at the pits A-55, A-70, R-61 (?) and W-17; N-S at the pits R-61 (?) and W-17; NW-SE at the pits A-55 and A-70. The direction of the hinge line (Skall, 1975, p. 40: 65°E) does not seem to be reflected in the water chemistry pattern near open pits, except for the drawdown effect exerted on the open pit S-65 by the dewatering of R-61. Instead, the direction of the Prebble and McDonald Fault system (45°E) seems to be indicated in the SW-NE hydrochemical pattern at the pits A-55, A-70, R-61 (?) and W-17. Santos (1975) found the directions SE-NW (pits K-57 and W-17), N-S (K-57, W-17) and E-W (W-17) indicated in the Zn + Fe chemistry of waters pumped.

ION AND SULPHUR ISOTOPE CHEMISTRY OF 'BLACK' WATER

Discharge of black water was observed at several open pits and at boreholes and natural discharge points in the area (see Fig. 3 -36C). The colour is caused by precipitation and suspension of black material in the discharging water. The 'black' water discharge has been investigated to some detail at the well hole WH 16 of J-69 (sample number WEY 290, Sept. 13, 1978). The results (Table 5.1) show a sulphate contents of about 1100 mg/l and a H_2S content of 16 mg/l. The black precipitate consists of metal sulphides, most of it iron sulphide. Lead, zinc, copper and nickel sulphides also may be present. The $\delta^{34}\text{S}_{\text{SO}_4}$ and $\delta^{34}\text{S}_{\text{HS}}$ isotope values in the water are normal with $+18.3\text{‰}$ and -24.3‰ , as is the sulphide isotope value for precipitation on rocks hit by the discharging water (-25.8‰).

Precipitate collected from the discharging water, however, has sulphide isotope value of $+8.8\text{‰}$. This value is similar to the $\delta^{34}\text{S}_{\text{MeS}}$ value ($+9.4\text{‰}$) of the galena ore sample J-69-1 (Table 5.2).

The isotopic value of $+8.8\text{‰}$ could be identified with erosion and corrosion of the orebody or with active precipitation processes. We prefer the latter interpretation for three reasons:

- (1) progressive darkening of the black water indicates active precipitation of sulphides,
- (2) the water is strongly reducing, and
- (3) $+9.4\text{‰}$ is the lowest $\delta^{34}\text{S}$ isotope value measured for the J-69 ore (Table 5.2); the average of 4 measured values is 12.5‰ .

The sulphide ions in the precipitate would originate from sulphate dissolved in water. Biochemical reduction in a semi-open system would shift the sulphur isotope value from $+18.3\text{‰}$ ($\delta^{34}\text{S}_{\text{SO}_4}$ in water) to $+8.8\text{‰}$ ($\delta^{34}\text{S}_{\text{MeS}}$ of precipitate in water). On the rock surface hit by the discharging waters open system conditions would exist for biochemical reduction, leading to a final $\delta^{34}\text{S}_{\text{MeS}}$ isotope value of -25.8‰ . The $\delta^{34}\text{S}_{\text{HS}}$ isotope value of -24.3‰ for the H_2S in water would indicate complete isotope fractionation in a first step of active biochemical reduction. This value would occur in closed, semi-open and open systems alike. The end products of biochemical reductions in open systems and closed systems under prevailing conditions would be about -25‰ and $+18.3\text{‰}$ respectively. Semi-open conditions would lead to intermediate values, e.g. $+8.8\text{‰}$.

Sample D in Table 5.3 indicates that at a black water discharge at open pit R-61 calcite had been precipitated as well, either during discharge or upon termination of pumping. Upon termination of discharge sulphides have probably been replaced by oxidized minerals (hematite, gypsum). Traces of Cu, Zn, Ni, Pb and Sr are still present.

BIOCHEMICAL PROCESSES

BACKGROUND

Weyer et al. (1979) showed that the ubiquitous occurrence of H_2S in the Pine Point region is caused by biochemical reduction of SO_4^{2-} dissolved in the groundwater. H_2S occurs everywhere in the area in groundwater

containing SO_4^{2-} . The level of H_2S can become very high (see Figure 3-52G) and on some occasions has blinded drilling crews. We have measured concentrations of up to 200 mg/l. It was noticed, that H_2S concentrations in pumping wells at some pits were considerably lower than what might be considered a background value ($\sim 5\text{-}20$ mg/l as compared to ~ 100 mg/l). Organic material to provide nutrients for sulphur-reducing bacteria seems to be plentiful (see Fig. 3-53, 3-54 and 3-55 and usually concentrated near orebodies.

In the course of our research project we have devoted further attention to the mechanism of H_2S generation, because H_2S concentration is one of the factors affecting mining safety and economy in general, particularly in subsurface mining. In 1981, a microbiological sampling program was conducted in cooperation with the Microbiology Laboratory of EPS in Edmonton. Sampling locations, microbiological counts of sulphur bacteria, and chemical data for the sampled waters have been recorded by Weyer and Horwood (1982). That report is attached as Appendix 4.

Two interesting aspects of the microbiological study are discussed in some detail below.

BIOCHEMICAL PROCESSES IN DEWATERING CHANNELS AT OPEN PITS

At pit S-65 and at several other pits the study came to some unusual results in regard to sulphur chemistry. In all pits the H_2S content in the water increased downstream in the dewatering channels (see Tables 5.4 and 5.5). This phenomenon has been documented in detail in the discharge channel of S-65 (Fig. 5-21 and Table 5.6). In the discharge channel close to the discharge points of the wells the H_2S content initially dropped slightly due to temporary aeration of the water. Unexpectedly the SO_4^{2-} content in the water increased downstream in the discharge channel by about 100 mg/l. This result gave rise to two questions (1) Where does the SO_4^{2-} come from and (2) how is the H_2S generated?

FIGURE 5-21

The SO_4^{2-} is probably generated by microbiological oxidation or by aeration, from intermediate species (e.g. sulphur or sulphite) which we did not expect to be present in any appreciable quantity. Possible microbiological processes to achieve this goal are listed in Table 5.7. If this concept holds true, it may be of general interest for the sampling and analysis of groundwater for sulphur species.

The H_2S is probably generated by bacteria within the yellow sulphur containing cover of the ditch bottom. Similar conditions occur at other pits as well. Although one might assume that this process is only a minor detail, it appears to be of great economic value to the mine. It seems to play an important role in the sealing of dewatering channels near open pits and further downstream, by plugging up pore space and thus reducing the return-flow of water from the discharge channels into the ground. This point is discussed further below.

CHANGES IN BACTERIAL POPULATION AND CHEMISTRY DURING THE K-77 PUMP TEST (1980)

Weyer and Horwood (1981) have reported changes in water chemistry, deuterium-isotope ratios and bacterial population during the pump test at open pit K-77 (Fig. 5-22).

FIGURE 5-22

The samples obtained, however, represent not fully the pre-pumping conditions; technical breakdown prevented the start of sampling till about four hours after pumping commenced.

FIGURES 5-23

FIGURES 5-24

FIGURES 5-25

Nevertheless, the data proved valuable in several respects. Figure 5-23 shows the recorded range of changes in major-ion chemistry. The plot clearly shows the diminishing role of calcium bicarbonate groundwater originating from the overlying till, and the increasing importance of CaSO_4 and NaCl in the chemistry of the water pumped. This effect is caused by transient hydrodynamic rearrangement of flow lines.

Figure 5-24 shows the changes in all parameters recorded. Of special interest to us are the changes recorded for the population of *thiobacilli* (Fig. 5-25). They show a decrease in the Most Probable Number (MPN) of *thiobacilli* per 100 ml, from the first sampling on October 4 to the last sampling on October 7 (from 1100 to 70; see Table 5.8). The decrease might have been found to be even larger, if a sample could have been taken before the start of the pump test. From the observed decrease it can be concluded that the bacteria *thiobacillus* and probably also other bacteria are concentrated near the orebodies, possibly because of a local enrichment in hydrocarbons. Pumping stress would gradually remove the bacteria as it replaces the local water with less-populated water drawn from the general environment in the aquifer.

RETURN FLOW FROM DEWATERING DITCHES AT OPEN PITS AT PINE POINT

It has been suggested in the past that return flow from dewatering channels toward the dewatering pumps (through the ground) would be a significant source for the water pumped at the mine pits. Weyer and Horwood (1979b, 1980a) investigated this matter in detail. The discharge-measurement methods used are described in Chapter 1. The

authors (ibid.) came to the conclusion that there is no significant return flow occurring from the channels investigated (at pits W-17, T-58, R-61, X-15, S-65). The methods used and results achieved can be demonstrated by the example of the S-65 dewatering channels (compare with Appendix 1). Figure 5-26 shows the arrangement of discharge measurement sites at the open pit S-65. At the time only the pump at well hole 1 was operating. The difference between measurements 1 and 2 was 0.3 l/s (0.4%) indicating that the measurements were practically identical (see Table 5.9 and Appendix 1).

FIGURE 5-26

Return flow from the dewatering channels, through underlying gravel, sand, silt, clay and karstic carbonates to the dewatering pumps, did not occur in significant amounts. This is due to the flow resistance of low-permeability clay layers, as well as to the sealing of pores of more permeable materials by biochemical precipitation of sulphur (Table 5.3).

COMPARISON OF PRE-MINING VS. MINING SITUATION

BACKGROUND

In the following an analysis of changes in groundwater flow in the Pine Point area is presented. It is partly based on a comparison of the pumping history in Pine Point with recorded changes in water levels in artesian boreholes and discharge from four karst springs in the area (for location of karst springs see Fig. 5-1; for location of formerly flowing holes see Figure 4-1). The effect of pumping on water levels at the Westmin Resources orebodies X-25 and R-190 has been discussed at the beginning of Chapter 5.

CHANGES NEAR OPEN PITS

The most prominent change near the open pits is the pumping stress itself, as manifested in the pumping history of Pine Point. Figure 5-27 shows that the rate of pumping was well below 30 000 USgpm ($1.9 \text{ m}^3/\text{s}$) before 1975 with a slight increase from 1971 to the beginning of 1975. From 1975 to 1977, pumping requirements increased from less than 30 000 ($1.9 \text{ m}^3/\text{s}$) to about 55 000 USgpm ($3.5 \text{ m}^3/\text{s}$), a level which was maintained with fluctuations into the middle of 1979, and then gradually reduced to about 40 000 USgpm ($2.5 \text{ m}^3/\text{s}$) by June 1980. No further pumping data are available to us at this time.

The associated increase in pumping stress opened karstic systems, not only mechanically (compare Fig. 3-40 and related discussions in Chapters 3 and 4), but also chemically, as a result of changes in the ionic strength of redirected groundwater flow. The latter process would lead to the dissolution of gypsum, especially if saline water were involved. Both processes increase the secondary permeability of the strata near the orebodies. The first process is irreversible.

REGIONAL EFFECTS

Effects at karst springs

Regional effects at some of the observed karst springs are recorded in Figure 5-27. Angus Tower spring is located about 45 km south of Pine Point and about 40 ft (12 m) higher in elevation than Halfway Spring which is located about 25 km south of Pine Point. In winters of 1975/76 and 1976/77 the springs south of the Pine Point continued to flow strongly throughout the winter (Fig. 5-27, arrows 1 and 2). Open water occurred for about 10 km downstream of Halfway Spring and for about 4 km downstream of Angus Tower Spring.

The sulphurous artesian borehole 104 and the nearby karst spring with sulphurous deposits (Fig. 5-28) were found dry on August 21, 1977 (Fig. 5-27, arrow 3) indicating depressurization in the underlying Presqu'île (compare Figs. 3-16 and 4-6). Both did not regain flow until the termination of our observations in August 1982.

FIGURE 5-27

FIGURE 5-28

FIGURE 5-29

In October 1977 the discharge from Angus Tower Spring and Halfway Spring was measured by Water Survey of Canada as 8 cfs (225 l/s) and 11 cfs (311 l/s), respectively (Fig. 5-27, arrow 4). From an observation of the banks it was clear that the discharge from the springs at that time was low compared to previous discharges (Figs. 5-29; 5-30). During the winter 1977/78 (Fig. 5-27, arrow 5) the flow rates were drastically reduced prompting us to install discharge observation stations at both springs in late spring 1978. In September and October 1978 (Fig. 5-27, arrow 6) Halfway Spring ceased to flow while the flow at Angus Tower Spring was reduced to about 18 l/s. Both springs did not maintain flow through the winter of 1978/79 (Fig. 5-27, arrow 7). On June 6, 1979, Halfway Spring was not flowing (Fig. 5-27, arrow 8). During the observation period from July 5 to Sept. 17, 1979 (Fig. 5-27, arrow 9) both springs were discharging 1.5-10.8 l/s (Halfway Spring) and 17.7-23.9 l/s (Angus Tower Spring). Both springs were not flowing during the summer of 1980 (Fig. 5-27, arrow 10; Figs. 5-31, 5-32 and 5-33). During 1980 water levels in the spring ponds at both karst springs (Angus Tower Spring and Halfway Spring) dropped by more than a meter below the minimum height at which outflow does occur. Angus Tower Spring did not discharge again from that time until August of 1982 when observations were discontinued. During 1981 water level in the spring pond at Angus Tower Spring stayed low and grassy and bushy vegetation covered the outlet of the creek (Fig. 5-34) and part of the creek bed in the vicinity of the gaging station (Fig. 5-35). Figure 5-36 shows vegetation cover in 1981 where in 1977 water (225 l/s) was flowing (compare Fig. 5-29). In August 1982 vegetation cover in the creek bed at Angus Tower Spring had become denser (Fig. 5-37 and 5-38). Water level in the spring pond was about 1.40 m below overflow conditions (Fig. 5-37, compare person in centre standing at water level of pond).

Halfway Spring was flowing again on June 4, 1981 (172.8 l/s). It maintained flow throughout the summer and fall (161.5 - 181.5 l/s). The spring was also flowing in August 1982.

FIGURE 5-30

FIGURE 5-31

FIGURE 5-32

FIGURE 5-33

FIGURE 5-34

FIGURE 5-35

FIGURE 5-36

FIGURE 5-37

FIGURE 5-38

Both years, 1981 and 1982, are considered dry years in the area. Hence renewed flow at Halfway Spring might reflect changes of pumping patterns at Pine Point Mines. These changes would first be evident at Halfway Spring and not at Angus Tower Spring because (1) Halfway Spring is closer (about 25 km) to Pine Point than Angus Tower Spring (about 45 km) and (2) the elevation of Angus Tower Spring is about 40 ft (12 m) higher than that of Halfway Spring.

*PPM data
unavailable*

FIGURE 5-39

FIGURE 5-40

Figures 5-39 and 5-40 compare 1978 and 1979 hydrologic data at the two karst springs with the Pine Point pumping history and climatological data. It appears that trends in the hydrologic behaviour of the springs follow the general trends of the pumping at Pine Point Mines Ltd. and specifically the pumping at W-17 and A-70. Recharge from snowmelt appears to dampen the effects with a time lag of 3-4 weeks. Increase of pumping at the open pit W-17 during the beginning of June 1978 and again at the beginning of May 1979 seems to be reflected, with some time lags, in the pressure data (water levels, discharges)

at Angust Tower Spring in 1978 and during 1979, in the water levels and pressure data at Angust Tower Spring and Halfway Spring. In 1979 spring recharge increased water levels and corresponding discharges to some degree. Also in 1979 pumping at the open pit A-70 was first started and gradually increased. At both pits (W-17 and A-70) direct connections exist with the deeper karst systems, because of the occurrence of salt water discharges.

The general pumping history at Pine Point Mines Ltd. (Fig. 5-27) during 1978, 1979 and possibly during 1980 shows a reduction of pumping by 15-20,000 USgpm ($1-1.3 \text{ m}^3/\text{s}$) in later winter before spring recharge occurred. At this time pumps are switched off because groundwater flow towards the pits is reduced and water levels in some pumping wells drop too low to maintain pumping. From this observation it can be concluded that the annual spring and summer recharge in the area has been pumped out by late next winter and 'groundwater mining' occurs from about January until the time of spring recharge. Hence, the effect of dewatering would spread laterally especially at this time in the annual cycle. This conclusion would explain why most of the pronounced changes in flow observed at the two karst springs seem to have occurred in late winter or early spring.

Observation from the occurrence of saline water

Salt water components are generally present in the Presqu'ile to the west of Buffalo River (Fig. 5-41) but, to the east of Buffalo River, were found only near breccia chimneys. This would preclude the natural existence of large scale lateral movement of salt water from west to east along the barrier reef structure.

FIGURE 5-41

In 1977 and 1978 saline water discharged from springs located between pumping open pits of Pine Point Mines and the shore of Great Slave Lake (Fig. 5-41 A, B). Hence, at this time, lake water had not been drawn

from Great Slave Lake towards the open pits. Increased dewatering in the North Trend may have caused flow from Great Slave Lake since then. In 1980 dewatering at A-70 had caused flow from Great Slave Lake since then. In 1980 dewatering at A-70 had caused two saline springs situated between the A-70 open pit and Great Slave Lake to fall dry (Fig. 5-41C, open circles).

FIGURE 5-42

Chloride and sulphate contents in the water of Little Buffalo River near its mouth shows an apparent dependence on salt water pumping at the open pit W-17 situated about 30 km to the west (Fig. 5-42, Tables 4.1 and 5.10). The general trend of pumping reversely effects the chemistry of the river water. In particular, the installation of 4 deep salt water pump (pumps 30, 31, 33 and 34 in Fig. 5-10 compare also Fig. 5-12 and 5-13 for salt water discharge seem to have caused a pronounced drop in SO_4^{2-} and also Cl^- contents in the river water upon commencement of pumping and an increase upon termination of pumping. This would suggest a cause and effect relationship. Salt water diverted from a southerly direction towards W-17 pumping would not enter the Nyarling River to the south of the Little Buffalo River to the SE. Hence a decrease in SO_4^{2-} and Cl^- concentrations would occur in the surface water flow of Little Buffalo River during salt water pumping at W-17.

Changes of flow at artesian boreholes

The artesian borehole Hay River Test No. 2 (table 1.3; Fig. 3-3: Fig. 4-1B: star ceased to flow during or shortly before 1981; it presumably had been flowing from 1930 until that time. It was sampled by us in 1978 and showed a pronounced build-up of sulphurous deposits. The hole is situated on the edge of the Hay River Canyon (see Fig. 4-2) about 90 km to the west of Pine Point.

The cessation of flow from the artesian borehole 104 has already been discussed earlier (for location compare Fig. 5.1). Two exploration boreholes east of the mouth of Buffalo River ceased flowing in 1981/82, probably sometime after pumping rates in the North Trend had been increased. Artesian boreholes north of Pine Point and at pit A-70 had ceased to flow earlier (compare Fig. 4-1B).

Conclusions

It appears certain that mine dewatering in the Pine Point area has exerted noticeable local and regional effects on groundwater levels and flow in the area. The area of depression appears to extend about 90 km to the west and more than 45 km to the south. Not much water, if any, seems to be drawn from Great Slave Lake.

Depressurization appears to affect flow in karst systems close to the surface within the Pine Point Group, within the deeper Lower Keg River Formation as well as flow in the Chinchaga Formation and in strata below the Chinchaga Formation.

In view of environmental considerations and potential economic benefits a method that might reduce the environment effects and the cost of dewatering is proposed in Chapter 7.

6. DIAGENETIC CHANGES AND THEIR INTERACTION WITH GROUNDWATER FLOW

DIAGENETIC CHANGES IN CARBONATES

The diagenetic sequence in carbonate rocks identified by Morrow (personal communication, 1982) appears to apply to the Pine Point area as well as to the Manetoe dolomite in NE British Columbia. Many or all of these events may have taken place in Middle Devonian time (for sequence of events see Chapter 1). It is likely, however, that the process of salt dissolution, with associated karst development, as well as glaciation have exerted significant modifying effects.

DEVELOPMENT OF POROSITY

Because of ongoing salt dissolution, brines would be available to maintain dolomitization near the solution front and elsewhere. Hence the rock-water interaction system of the region should not be regarded as static but as a dynamic system with a tendency to create new porosity in some areas (e.g. areas of strong groundwater flow) while reducing permeability in other areas. Geologic evidence for the local reduction of permeability would be: precipitation of minerals on fracture surfaces and in vugs, collapse into solution cavities and associated blockage of karst systems by collapse material, as well as internal sedimentation by mud and sand. In toto, however, the system now seems to have a tendency to increase the overall permeabilities.

Because of glaciation (Laurentide Ice Sheet) and formation of interglacial lakes, groundwater flow directions and therefore chemistry in the Pine Point area were changed several times. During glaciation, groundwater flow was from the east; with varying magnitudes. Between glacial and interglacial times the groundwater chemistry fluctuated between fresh, sulphurous (?) and saline waters and Ca-Na-Cl brines. Therefore the necessary chemical ingredients for both enhancement and reduction of porosity were available; it is difficult to estimate which process predominated. Mechanically, increased potential gradients and subsequent cleaning out of karst systems, as well as hydrodynamic blowouts, created higher porosities and permeabilities.

Changes in the elevation of discharge areas in connection with interglacial lakes modified the flow of reducing sulphurous and saline groundwater from the south towards Pine Point. In the Pine Point area itself, salt water penetrated from deeper layers upwards through all of the Devonian strata. Isostatic rebound caused falling lake-water levels and subsequent changes in groundwater flow direction, intensity and thereby in chemistry. More local, oxidizing groundwaters recharged and penetrated part of the Devonian sequence. A counter play developed, displacing the oxidizing front vertically up and down and also laterally.

ORE GENESIS

Naturally the sequence of more or less drastic chemical and hydrodynamic changes exerted a profound influence on diagenetic events. It is surprising that the orebodies at Pine Point basically show an unusually simple sphalerite and galena mineral assemblage only. It is conceivable that this condition may be a reflection of a 'distillation'-like process of repeated re-dissolution and re-precipitation of ore minerals.

Carrying this speculative line of thought a little further, it may be assumed that the materials in the orebodies have originated in Devonian time, and that they have been re-dissolved and re-precipitated selectively since then, in such a manner that there is little or no evidence of the primary situation left. Pb and Zn may also have been dissolved from the Precambrian rocks by deep saline groundwater. The metals then have migrated into the vicinity of the existing ore zone and precipitated by mixing or other appropriate chemical mechanisms, as for example precipitation caused by biochemical or other means of H_2S production.

Salt dissolution may have contributed to the formation of saline waters of a Na-Cl type penetrating the Precambrian beneath the sedimentary Devonian cover. In this case groundwater flow would have been from the south. Using Davidson's (1966) model, the origin of the metals may also have been in the dissolved salt; Roedder (1968a) supported this hypothesis.

There are indications that fluid inclusions in the Pine Point ore and in some of the associated carbonates contain CaCl_2 as inferred from Roedder's (1968a) and Vasquez's (1968) results. We have shown in Chapter 3 that Ca-Na-Cl waters are present in the Canadian Shield east of Pine Point. We have also found that during glaciation these waters were probably flowing from the east, through the McDonald, Prebble and other fault systems, towards Pine Point.

At least 70 Pb-Zn occurrences and deposits are known to exist to the east of Pine Point in the area of the topographical map sheets 1:250 000 NTS 75E, F, K, L, O, P and 85 H, I, (see Fig. 6-1). There are no deposits known in the area of the map sheet NTS 75J. All occurrences and deposits are listed in the Geological Survey of Canada's computer file CANMINDEX (Picklyk et al., 1978) and three additional GSC computerized data systems (D. Sangster, 1982, written communication). Rheinhardt (1969) described the occurrence of Pb-Zn-deposits in relationship to the McDonald Fault system. Further occurrences are described by Stockwell (1931), Henderson (1937), Brown (1950), Lord (1951), Barnes (1952), Irwin (1955), Baragar (1962, 1963), Thorpe (1966, 1972), Reinhardt (1969), McGlynn (1971), Padgham (1975, 1976) and Gibbins (1977). Pb and Zn may have been transported by Ca-Cl-groundwater from the area of these showings towards Pine Point.

FIGURE 6-1

From all the above conditions one may assume that ore precipitation also may have been important during the Pleistocene. This inference is unconventional but is supported by some of the evidence for Pleistocene diagenetic events described in Chapter 3 under 'Karst features near orebodies'. A similar hypothesis has been presented by McGinnis (1968) for the MVT deposits in the Tri-State district. Occurrence of HCl associated with ore precipitation would have provided an additional mechanism for porosity and permeability enhancement. Investigation of the black water (Chapter 5) provided indications that some precipitation of ore minerals may even occur presently.

DIAGENETIC CHANGES IN NON-CARBONATE ROCKS

It has been shown (Chapter 3) that rock-water interaction with highly saline waters can cause an increase in porosity and permeability in anhydrite and gypsum strata. This can also occur in gneissic or granitic rocks containing Ca-feldspars.

The chemical dissolution process described earlier (Chapter 3, Fig. 3-27) for CaSO_4 probably applies in a similar manner for Ca-feldspars. Dissolution of granitic boulders on the Salt Flats near Fort Smith has been described in Chapter 4.

It appears that, in the Pine Point area, salt dissolution and the associated formation of highly saline water and brine are important processes that cause diagenetic changes in the surrounding rocks by the action of groundwater.

7. REDUCTION OF PUMPING REQUIREMENTS

ECONOMIC AND ENVIRONMENTAL CONSIDERATIONS

In the Pine Point mining district the position of the orebodies is related primarily to karst collapse and solution features. The karst systems are highly-permeable transmitters of groundwater flow.

Hence, the cost of dewatering at Pine Point Mines has shown a pronounced increase with increasing mining depth and the positioning of open pits in low-lying areas. At some open pits the cost of dewatering constitutes more than 10 percent of the total mining costs. It is to be expected that the dewatering cost will rise further (Vogwill, 1976) if mining is commenced close to the Buffalo River and in other, low-lying areas.

Because of northern isolation the amount of energy available for pumping is limited. Unexpectedly-high groundwater inflow has on occasion made it difficult to achieve design drawdown within the projected timespan (open pit R-61 and A-55).

Groundwater in the lead-zinc district of the Great Slave Lake area releases significant amounts of poisonous hydrogen sulphide gas at open pits and in subsurface mine workings. A significant reduction of groundwater seepage to the mining areas therefore could also significantly reduce the amount of hydrogen sulphide released. Thereby the operation of deep subsurface mines could be made practicable.

In Chapter 5 it was shown that pumping at Pine Point Mines may affect groundwater flow more than 45 km to the south and even more to the west. 90km
The lowering of the groundwater table and changes in groundwater flow with associated cleaning out of sediment-filled cavities exert an additional man-made stress on the ecosystems south of Great Slave Lake. This stress could be reduced by a reduction in the withdrawal of groundwater.

*At odds with
postulation of
main flow
from south*

Thus economical, technical and environmental considerations would all favour a search for alternative methods of dewatering that could reduce both the cost of dewatering and the amount of water pumped.

In this chapter a method is described which has been used for several decades, with both technical and economic success (Schmieder, 1978b), to reduce groundwater flow in karst systems near subsurface lignite and bauxite mines in Hungary (Schmieder et al., 1975).

KARST WATER PROBLEMS IN SUBSURFACE LIGNITE MINES IN HUNGARY

Within the Hungarian Central Mountains in the Transdanubian region of Hungary, subsurface mining of lignite encounters water inflows from triassic karst. In the mining districts of Dorog, Tatabánya, Dunbar and Balinka (Fig. 7-1) the water originates in karstic layers below the coal; in the district of Ajka it originates in karstic layers both below and above the coal. Out of 1500 cases, the highest rates of groundwater inflow occurred in the mining districts of Tatabánya and Dorog where discharge rates reached up to $110 \text{ m}^3/\text{min}$ according to Schmieder (1978a). Willems et al. (1963) list technical details of water inflows in the Dorog district (427 cases) and Tatabánya district (197 cases). The frequency distribution of the inflow rates is lognormal, showing a 40 percent peak at about $1 \text{ m}^3/\text{s}$ for the Dorog district and a 35 percent peak at about $0.4 \text{ m}^3/\text{s}$ for the Tatabánya district (Schmieder, 1978 a Fig. 1a).

From the results of tracer tests, groundwater flow velocities within the karst system have been estimated to be between 50 and 100 m/h and, in some cases, between 100 and 160 m/h (Willems and Dallos, 1961). Elevated outcrops of the karst in the Hungarian Central Mountains are regarded by Ajtay et al. (1962) and Deák (1979) as the recharge areas for the regional groundwater flow systems (Fig. 7-2). From there the water is considered to flow down-dip through the 800-1000 m thick karst sequence consisting of limestone and dolomite. In the mining district of Dorog, the overburden is 200 to 400 m thick, in the Tatabánya district it is 150-300 m thick.

According to Milde (1963) the water pressure can be up to 80 atm (1175 psi; 8.1 MPa; 825 m or 2700 ft of water). This pressure is surprisingly high, although general hydrodynamic considerations, under the prevailing geologic and topographic conditions, would lead one to expect the undisturbed hydrostatic pressure in the deeper parts of the karst to be well in excess of 40 atm. Initial hydraulic gradients between the groundwater in the karst systems and the mine workings are reported to be up to 50 to 60 m/m in the mining districts discussed (Schmieder, 1978 a).

Average transmissivities are $3.0 \times 10^{-2} \text{ m}^2/\text{s}$ in the karstic limestone layers of the Dorog area; in the Tatabánya district they are $4.2 \times 10^{-2} \text{ m}^2/\text{s}$ in karstic limestone and $2.1 \times 10^{-2} \text{ m}^2/\text{s}$ in karstic dolomite (Schmieder, 1971; Kovács and Associates, 1981, p. 836).

Average porosities reported for the carbonate rocks in the Tatabánya district are 9.0 percent at the surface and 2.2 to 2.5 percent in 60 to 80 m depth; in the Dorog district the average porosity is 1.32 percent (Kovács and Associates, 1981, p. 829). A frequency distribution of the open width of fractures and cavities in the Dorog limestone shows a distinctly bimodal lognormal distribution, with a 22 percent peak at about 3 cm aperture and a second one at about 70 cm aperture in about 10 percent of the cases (Schmieder, 1978, Fig. 1b). The maximum width recorded exceeded 10 m.

Immediately above the karst are confining clay layers from 0 to 50 m in thickness. The clay layers usually protect the overlying mined lignite beds from water inflows. Tectonic structures (96% of the cases; Vigh and Szentes, 1952) and "windows" without clay cover can, however, act as conduits for major water inflows as shown in figure 7-3.

At present, total withdrawal of groundwater from the karstic aquifers in the Transdanubian Mountains far exceeds the natural recharge. The water withdrawal exerts an effect on the operation of thermal spa's in Budapest, more than 40 km to the east, necessitating restrictions

in pumping and an increase in the application of passive-preventive dewatering methods (Schmieder, 1978b).

"ACTIVE" AND "PASSIVE" DEWATERING METHODS

In Hungary the subsurface mining of lignite started well before 1890. Considerable experience in the dewatering of karst has been accumulated during the last 50 years (Kesserű, 1978) and special cost-reducing methods have been developed. Research and consultation for planning are in the hands of the Hungarian Research Institute for Mining (BKI: Bányászati Kutató Intézet) in Budapest. Ajtay et al. (1962) and more recently Schmieder et al. (1975), in two textbooks, summarized the Hungarian methods for the reduction of permeability of karst systems near subsurface lignite and bauxite mines.

In general, the Hungarians differentiate between "active" and "passive" methods for dewatering of mines. "Active" methods include pumping water from within and around mining facilities; "passive" methods are those which reduce the water inflow, and thereby the required rate of pumping. Because of reduced costs for energy, the passive-preventive methods tend to be beneficial for the mining economy, if large amounts of groundwater would otherwise percolate to the mine workings. They also reduce the environmental effects of dewatering (Schmieder, 1978b).

There are several "passive" dewatering methods available, such as the construction of grout curtains around open pits or subsurface mine workings, and others. Recently they have been summarized by Kápoli et al. (1978, Fig. 5). Grouting methods have not proven to be very successful in karst systems with large openings. In fact, one of the primary conditions for successful application of grouting is the absence of open karst systems.

The Hungarian method of sand and gravel injection, however, requires relatively open karst systems to be effective. It will not work in rocks with narrow-fracture permeability only.

SAND AND GRAVEL INJECTION TECHNOLOGY

A mixture of sand (60%) and crushed and pea-sized gravel (40%) is injected through a borehole into an open karst system. Often hydrochloric acid is used to widen the solution channels around the borehole. The total amount of material injected in a single borehole is usually between 2000 and 5000 m³. Up to 1962 the maximum volume injected in a single borehole in Hungary was 240 000 m³ (Milde, 1963).

The sand and gravel mixture is suspended in water. The sand is normally hydraulically mined with monitors and transported to nearby boreholes through pipelines (Fig. 7-4). Crushed gravel is added in the appropriate quantities. In cases with flowing conditions the inlet for the gravity-feed system is placed on elevated ground near the borehole.

To be successful, the method should produce an increase in the resistance to flow in the solution channels (Fig. 7-5). The use of crushed gravel with sharp edges helps to anchor the sand-gravel mixture within narrow but still open parts of the solution channels. Cement can be added to strengthen the plug. The velocity of the groundwater flow is decreased, as is the flow rate. If all important solution channels are filled with the sand-gravel mixture, the total flow to the mine workings will be reduced significantly and it may even be virtually eliminated, depending on the geometry of the solution channels and the presence of narrow fractures.

In 54 cases of water inflow, mine workings in the Dorog district had been partly or completely flooded (Schmieder, 1978b). After injection of the sand-gravel mixture they were successfully pumped dry again. The exact position for the injection wells was determined using, besides other information, micro-tectonic data on file from geologic and hydrogeologic exploration activity.

SUCCESS RATE OF PASSIVE DEWATERING IN HUNGARIAN MINES

In the Tatabánya mining district the success rate of the sand-gravel injection method has been low in dolomite areas because there the water flows through numerous narrow fractures. These fractures do not allow penetration of the sand-gravel mixture. For limestone karst Kálmán (1951) presents diagrams of two cases where the inflow had been decreased from 1045 l/min to 45 l/min and from 3500 l/min to 400 l/min.

Within the open karst systems of the Dorog mining district, water inflows have been shut off completely in 50 percent of the cases, according to Milde (1963).

The same author also reported two cases of partial success. In the first case a sudden water inflow was reduced from $10 \text{ m}^3/\text{min}$ to $5 \text{ m}^3/\text{min}$; in the second case, a water inflow of $20 \text{ m}^3/\text{min}$ was reduced to $4 \text{ m}^3/\text{min}$ after an injection of 9000 m^3 of solid material. In the latter case the injection was still continuing.

In general, during a 30 year period, passive-preventive dewatering methods had an overall efficiency of 90 to 92 percent; after sealing, only 8 to 10 percent of the previous yield had to be pumped from the mines (Schmieder, 1978b).

CONDITIONS FOR THE USE OF THE SAND-GRAVEL INJECTION METHOD IN THE PINE POINT AREA.

From the previous discussions it appears that the Hungarian sand-gravel injection method might be a technically viable alternative or addition to the present pumping system used in the Pine Point area.

Water and sand for hydraulic mining seem to be available within reasonable distances from the orebodies and could be transported to the well sites in slurry pipelines, using gravitational force. Detailed geologic mapping for sand would be necessary. Crushed gravel could be produced from available dolomite or limestone spoil.

As far as the karst systems are concerned it appears from previous drilling experience that the solution channels in the carbonate rocks are wide enough to permit the flow of sand-and-gravel slurry away from an injection hole. Cavities of more than 10 m width have been encountered in the area.

The results of the geological and hydrogeological evaluation (Chapters 3 and 5) indicate that the solution channels and collapse zones are extensive and interconnected (see also Durston, 1979, Weyer, 1982, Weyer et al., 1979). They widely extend horizontally and, possibly to a lesser degree downwards.

Repeated hydrochemical investigations at open pit W-17 in 1977, 1978 and 1979, under different pumping-stress conditions, showed that karst systems with distinctly different water chemistry are interconnected near the orebody (Weyer and Horwood, 1979a; Weyer and Horwood, 1980b). Similar observations have been made during the 1980 pump test at K-77 (Weyer and Horwood, 1981). Observations on air flow in and out of piezometers during the K-77 pump test (Weyer and Horwood, 1981) also indicated a high degree of interconnection of solution channels in the upper portion of the bedrock section.

Hydrochemical investigations at the open pits W-17 and R-61 (Weyer, 1978b), and an evaluation of the spread of the dewatering cones (K. Durston, personal communication, 1980) around individual open pits and in areas with several pits close to each other (W-17 and X-15; T-58, R-61 and S-65) indicate that the groundwater flow is locally affected by geologic structures. This condition could limit the volume of sand-gravel mixture required, as compared to a geologic condition with a uniform spatial distribution of karst channels.

The temporary rebound of drawdown curves (Fig. 3-40), which frequently occurs during pumping tests at Pine Point Mines, can be taken as an indication of the removal, by pumping stress, of low-permeability "plugs" within the karst channels. Such "plugs" could serve to hold the sand-gravel mixture initially in place within the solution channels.

From past experience and from general hydrodynamic and geologic conditions in the area it appears that the hydraulic-head differences between the bottom of the open pits and the water in the karst systems in pre-mining conditions did not exceed 100-130 m (300-400 ft.); because of previous dewatering, they are much smaller under the present conditions of lowered groundwater tables. Hungarian experience indicates that the magnitude of the hydraulic-head differences prevailing in the Pine Point area should not prevent a closure of portions of the karst systems by sand-gravel injection. This would be particularly true if the sand-gravel mixture is injected before pumping commences.

It is probable that several injection holes, to different depths, will be necessary to reduce lateral and upward groundwater inflow to an open pit significantly. Geometrically, the sealing procedure needs to be applied in a half-sphere penetrating the surrounding rocks as well as the deeper layers beneath the pit.

Having discussed only positive aspects so far, a word of caution is necessary: only a test can determine the technical viability of sand-gravel injection at Pine Point Mines or any other mine in a karst area. It is quite clear that pumping may still be necessary at a reduced rate after sand-gravel injection, either with sump pumps only or with supporting dewatering wells. This brings up the question of whether suitable sand-resistant pumps are available.

Explosives used during mining would have to tolerate the presence of water. The addition of siliceous or calcareous sand to the ore material might pose unwanted technical problems in the milling process. The period of change-over in dewatering procedures might cause an interruption in mining, if unexpected problems arise. Refined geologic and hydrogeologic procedures need to be developed to determine the distribution of solution channels around and within the orebodies and the relationship of this distribution with other geologic parameters.

Concerning the economic viability, a detailed assessment of the costs involved and of the short-term and long-term benefits would be necessary. Consideration should be given to the limitations in energy available for pumping and the probable occurrence of orebodies in highly-permeable rocks such as those encountered during a pump test at the ore deposit R-190 of Westmin Resources west of Buffalo River (Golder Associates, 1980).

The Hungarian sand-gravel injection method in its present form, or a modified version of it, constitutes a potential method for reducing the pumping requirements at Pine Point Mines and others, in similar settings, by 90 percent.

In regard to deep subsurface mining in the area, the application of passive dewatering methods could prove a cornerstone for the alleviation of the hydrogen sulphide problem.

From a general point of view it is clear that the adoption of a passive dewatering system could benefit the image of the mining industry south of Great Slave Lake. From an environmental point of view, passive methods would be desirable because they would reduce the extent of the dewatering effects. The latter aspect would become more important if additional mines were to open on leases to the east (Shell) or west (Western Mines; Cominco, Hay West) of Pine Point. Recommendations for further investigations are contained in Weyer (1981b).

8. CONCLUSIONS

DIAGENESIS, KARST DEVELOPMENT AND DOLOMITIZATION.

By necessity a holistic approach had to be adopted in the study of the interconnected geological and hydrogeological systems in the Pine Point area. Diagenetic processes from Late Givetian on were important participants in the formation of local and regional fluid flow systems as well as porosity and permeability systems. The water chemistry, the flow directions and the magnitude of flow in turn determined directions and magnitude of such diagenetic processes, as dolomitization, karst development and ore accumulation. Dissolution of salt layers in the Mirage Point Formation was found to have been of major importance to some of the diagenetic processes setting the stage for the groundwater landscape as it appears today. Strong effects by glacial events were identified, in connection with the 20 to 30 glacial ice sheets that have covered the area as well as with the interglacial lakes covering parts of the area periodically.

Glacial events affected the diagenesis by reversals of flow directions (up vs. down) and by drastic changes in groundwater chemistry (saline, sulphurous and fresh; oxidizing and reducing state). Re-dissolution and re-precipitation of secondary minerals was and is still effected by the inter-play of these conditions. The processes are still active as evidenced by continuing karst development, biochemical activity and oxidation of high-level orebodies. Glacially initiated hydrodynamic blowouts modified the karst and created additional highly permeable vertical pathways between the Chinchaga Formation (and possibly deeper layers) and the surface. These pathways are still active today.

Karst systems south of Great Slave Lake are regionally extensive and interconnected. They are found in the Mirage Point, Chinchaga and Lower Keg River Formations, in the Pine Point Group (including the Muskeg Formation), in the Watt Mountain Formation and also in the Slave Point Formation.

The postulate of a significant permeability impedance between systems in the Presqu'ile and other facies of the Pine Point Barrier on the one hand and the gypsum karst in Wood Buffalo National Park on the other hand does not seem to hold up. Presqu'ilized rocks have been found close to Wood Buffalo National Park. Furthermore in the Muskeg Formation, the interbedded strata of J-facies dolomite, anhydrite and gypsum also cannot be considered an effective barrier for groundwater flow on a regional scale.

Mineral deposits and showings of sphalerite and galena occurred much farther south than could be expected on the basis of the ruling hypotheses on ore genesis. This may suggest additional orebodies farther to the south than assumed so far. There are indications of promising mineral showings in some of the exploration boreholes west of Hay River (Hay West) which may in the future extend the zone of economical mineral deposits toward the Hay River and beyond.

Although, there are not enough supporting data available so far, groundwater flow caused by glaciation may have had a modifying effect on the genesis of the orebodies. During glacial times CaCl-brines enriched in metals may have been flowing from the Canadian Shield into the highly permeable systems of the Pine Point Barrier, remobilizing and reprecipitating existing PbS and ZnS mineralization.

GROUNDWATER FLOW AND CHEMISTRY

The chemistry of the groundwater in the area encompasses systems dominated by bicarbonate in the till material, by sulphurous water in the upper parts of the karst, and by saline and sulphurous water in the deeper strata and the lower karst.

Groundwater flow in the area reaches down to the granite wash and the Precambrian. The highly permeable granite wash and the upper diagenetically altered part of the Precambrian basement act as deep aquifers, as do the Cold Lake equivalent breccia and a deeper breccia levels. Fault systems in the Precambrian extend from the east towards Pine Point and also from the south into the Pine Point area. They probably are important

pathways for deeper penetrating groundwater flow and may also have carried glacial groundwater flow in connection with the Laurentide Ice Sheet (especially the McDonald Fault system).

There are strong indications for a highly permeable zone occurring in the Pine Point Barrier. This zone strikes about NE-SW and extends locally into the Chinchaga Formation and probably deeper. Hence, this system appears to provide upward leading conduits for deeper saline groundwater flow, causing the mixing of groundwaters of differing chemistry in the Pine Point Barrier. This is indicated by the results of hydrochemical investigations at the orebodies W-17, A-70, A-55 and R-190. These passageways may also have had some bearing on the genesis of the orebodies.

EFFECTS OF MINE DEWATERING AND RECOMMENDATIONS

Upon commencement of mine dewatering, groundwater flow directions and chemistry first changed locally and later also regionally. Depressurization of aquifer systems first progressed most strongly in an E-W direction along the Presqu'ile structures, leading to the cessation of flow at a major karstic spring on the bank of the Buffalo River and the adjacent artesian borehole 104. Since then the depressurization effect may have reached as far west as the Hay River where a flowing borehole (Hay River Test No. 2) on the rim of the Hay River canyon ceased to flow in 1981. It might be possible, however, that after fifty years, an infilling of the hole caused the cessation of artesian flow. Observations at major karst springs located about 25 and 45 km south of Pine Point indicated an effect of the dewatering as early as 1977. Both springs dried up in 1980. However, one spring commenced flowing again in 1981 probably reflecting a reduction in pumping at Pine Point Mines. It seems that the dewatering effect has reached and progressed beyond the karst spring near Angus Tower. In 1981 and 1982 two artesian exploration boreholes and a saline creek (our gaging station 3), all in the area of the mouth of Buffalo River, ceased to flow temporarily..

Water discharged at well heads is in a state of changing chemical balance. Chemical and biochemical reactions lead to the precipitation

of carbonates and sulphur minerals on the bottom of the dewatering channels producing a low permeability coating. Thus, return flow of water from the channels downwards into the karst is greatly reduced, to less than a few percent at most. In fact, no water losses were detected in accurate discharge measurements along several of the discharge channels.

Groundwater flow from Great Slave Lake towards dewatering pumps at Pine Point seemed not to be significant in 1978 and probably never was. As late as October 1978 there were springs flowing on the beach in the bay south of Slave Point and north of Pine Point Mines, discharging sulphurous water (samples 362 and 363) with a significant content of chloride. Thus a 'curtain' of upwelling sulphurous and saline water would have impeded groundwater flow from Great Slave Lake towards the Pine Point pits.

At the time of salt-water pumping at the open pit W-17, salt water discharge into the Little Buffalo River was obviously subdued. Before commencement of pumping, salt content in the Little Buffalo River was comparatively high. It increased again upon discontinuation of the W-17 dewatering. Hence pumping of salt water seems to have exerted a regional effect on the deeper parts of the groundwater flow systems as well.

Although our data clearly indicate a strong effect of the pumping on the groundwater flow, as had to be expected in a pronounced karst system, further observation of the karst springs and further data evaluation would be beneficial.

Costs for dewatering have increased dramatically because of rising energy costs and the mining of deeper lying orebodies. Hence, it would be useful to assess present dewatering methods used at Pine Point Mines in comparison with other methods, such as the one described in Chapter 7 of this report. A reduction of groundwater flow to the pits and future subsurface mine workings would in turn reduce costs and also limit environmental effects. This could become especially significant if open pits or subsurface mine workings were to be opened farther to the west of Pine Point.

It is certain, that upon complete cessation of dewatering, the groundwater level in some areas will not recover to the pre-mining situation, because the permeability of the karstic systems has been increased irreversibly. To some degree the process was already active naturally and pumping accelerated this process by introducing additional mechanical and perhaps also chemical stresses. One can expect that the discharge from the two karst springs south of Pine Point will not completely return to the conditions existing before the commencement of pumping.

9. REFERENCES

- Adams, J.E., and Rhodes, M.L. 1960. Dolomitization of seepage refluxion. Bulletin, American Association of Petroleum Geologists, v. 44(12), p. 1912-1920.
- Agricola, Georgius, 1556. De re metallica.
- Ajtay, Z., Vigh, F. and Willems, T., 1962. Bányavizek Elleni Védekezés (Protection against mine water). Budapest.
- Alberta Environment, 1977. Methods manual for chemical analysis of water and wastes. Edmonton.
- Alberta Research Council, 1970. Bedrock geology of northern Alberta. ARC, map 35, scale 1:500,000, Edmonton.
- Al-Hashimi, W.S. and Hemingway, J.E., 1973. Recent dedolomitization and the origin of the rusty crusts of Northumberland. Journal of Sedimentary Petrology, v.43 (1), p. 82-91.
- Alldrick, D.J., Batchelor, E.W., Collins, J.A., Lantos, E.A., Rhodes, D., Webb, R.J., and West, J.M., 1981. Pine Point lead-zinc deposits - District of Mackenzie, N.W.T. Field guides to geology and mineral deposits. Calgary 81' GAC, MAC, CGU 1981, p. 155-157.
- Alldrick, D.J., 1982. Geology of the A-55 orebody. Excursion guide, field trip D. 9th International Geochemical Exploration Symposium, Saskatoon, May 12-14, 9p (Report dated May 7, 1981)
- American Commission on Stratigraphic Nomenclature, 1970. Code of Stratigraphic Nomenclature (2nd. ed.) AAPG, 21p.
- Anderson, G.M. 1975. Precipitation of Mississippi Valley-type ores. Economic Geology, v. 70, p. 937-942.
- Anderson, G.M., and Macqueen, R.W., 1982. Ore deposit models - 6. Mississippi Valley-type lead-zinc deposits. Geoscience Canada, v. 9(2), p. 108-117.
- Andrews, J.T., 1970. Present and postglacial rates of uplift for glaciated northern and eastern North America derived from postglacial uplift curves. Canadian Journal of Earth Sciences, v. 7, p. 703-715.
- Anonymus, 1980. Schedule of wells, Northwest Territories and Yukon Territory. Dept. of Indian and Northern Affairs. Canada, Ottawa.

- Baadsgaard, H., Campbell, F.A., Cumming, G.L., Evans, T., Kanasewich, E., Krouse, H.R., Robertson, D.K., and Folinsbee, R.E., 1966. Isotopic data from the Cordillera and Liard basin in relation to the genesis of the Pine Point lead-zinc deposits. Royal Society of Canada, June Meeting, 1965, (abstract).
- Badham, J.P.N., 1978. The early history and tectonic significance of the East Arm graben, Great Slave Lake, Canada. *Tectonophysics*, v. 45, p. 201-215.
- Banner, J.A., and van Everdingen, R.O., 1979. Automatic time-lapse camera systems. Environment Canada, IWD Technical Bulletin no. 112, Ottawa, 20p.
- Baragar, W.R., 1962. Mineral Industry of District of Mackenzie and part of District of Keewatin, 1961. Geological Survey of Canada, Paper 62-1.
- Baragar, W.R., 1963. Mineral Industry of District of Mackenzie. Geological Survey of Canada, Paper 63-9.
- Baranowski, S., 1973. Geyser-like water spouts at Werenskioldbreen, Spitsbergen. *International Association of Scientific Hydrology*, Publ. 96, p. 131-133.
- Barnes, F.Q., 1952. McLean Bay map-area. Geological Survey of Canada, Paper 52-5.
- Barton, P.B., 1967. Possible role of organic matter in the precipitation of Mississippi-Valley ores. *Economic Geology*, Mon. 3, p. 371-378.
- Bassett, H.G., 1952. Correlation of Devonian sections in northern Alberta and Northwest Territories. Unpublished Ph.D. - thesis, Princeton University, 175p. (with maps).
- Bauer, F., 1961. Kalkabsätze unter Kalkalpengletschern und ihre Bedeutung für die Altersbestimmung heute gletscherfrei werdender Karrenformen. *Zeitschrift für Gletscherkunde und Glazialgeologie*, v. IV(3), p. 215-225.
- Beales, F.W., 1975. Precipitation mechanisms for Mississippi Valley-type ore deposits. *Economic Geology*, v. 70, p. 943-948.
- Beales, F.W., and Jackson, S.A., 1966. Precipitation of lead-zinc ores in carbonate reservoirs as illustrated by Pine Point ore field, Canada. *Transactions of the Institution of Mining and Metallurgy*, v. 75, p. B278-B285; discussed in v. 76, 1967, p. B130-B136, p. B175-B176.
- Beales, F.W., and Jackson, S.A. 1968. Pine Point - a stratigraphical approach. *Can. Inst. Min. and Met.*, v. 61, no. 675, p. 867-878.

- Beales, F.W., and Oldershaw, A.E., 1968. Evaporite-solution brecciation and Devonian carbonate reservoir porosity in Western Canada. *American Association of Petroleum Geologists Bulletin*, v. 53(3), p. 503-512.
- Bell, J.M., 1929. The Lead-zinc deposits near Pine Point, Great Slave Lake. *Trans. Canadian Institute Mining and Metal.*, v. 32, p. 122-139.
- Bell, J.M., 1930. Lead-zinc zones of Great Slave Lake. In: *Geological Survey of Canada. Lead and zinc deposits of Canada. Economic Geology Ser. no. 8*, p. 219-224.
- Bell, J.M., 1931. The genesis of the lead-zinc deposits at Pine Point, Great Slave Lake. *Economic Geology*, v. 26(6), p. 611-624.
- Bell, R., 1902. Mackenzie District. *Geological Survey Canada, Annual Report, 1899*, n ser., v. 12, pt.A, p. 103-110.
- Belyea, H.R., 1971. Middle Devonian tectonic history of the Tathlina Uplift, southern District of Mackenzie and northern Alberta, Canada. *Geological Survey of Canada, Paper 70-14*.
- Belyea, H.R., and Norris, A.W., 1962. Middle Devonian and older Paleozoic formations of southern District of Mackenzie and adjacent areas. *Geological Survey of Canada, Paper 62-15*, 82p.
- Billings, G.K., Kesler, S.E., and Jackson, S.A., 1969. Relation of zinc-rich formation waters, northern Alberta, to the Pine Point ore deposit. *Economic Geology*, v. 64(4), p. 385-391.
- Bishop, R.A., 1954. Saskatchewan exploratory progress and problems. In: Clark, L.M. (ed.): *Western Canada Sedimentary Basin (Ralph Leslie Rutherford Memorial Volume)*. American Association of Petroleum Geologists, Tulsa.
- Bock, E., 1961. On the solubility of anhydrous calcium sulphate and of gypsum in concentrated solutions of sodium chloride at 25°C, 40°C, and 50°C. *Canadian Journal of Chemistry*, v. 39, p. 1746-1751.
- Bogacz, K., Dzulyński, S., and Haranczyk, C., 1973. Caves filled with clastic dolomite and galena mineralization in disaggregated dolomites. *Ann. Soc. Géol. Pologne*, v. 43, p. 59-72.

- Borchert, H. and Muir, R.O., 1964. Salt deposits: the origin, metamorphism, and deformation of evaporites. D. Van Nostram & Company Ltd., Toronto, Canada, 338 p.
- Brandon, L.V., 1965. Groundwater hydrology and water supply in the District of Mackenzie, Yukon Territory, and adjoining parts of British Columbia. Geological Survey of Canada, Paper 64-39.
- Brashears, M.L., 1968. Groundwater conditions and dewatering of ore pits at Pine Point, N.W.T., Canada. Legette, Brashears and Graham Report to Cominco Ltd., 57p.
- Brashears, M.L., and Slayback, R.G. 1971. Pumping test methods applied to dewatering investigations at Pine Point Mines, N.W.T., Canada. A.I.M.E. Annual Meeting, New York.
- Bredehoeft, J.D. and Hanshaw, B.B., 1968. On the maintenance of anomalous fluid pressure. I. Thick-sedimentary sequences. Geological Society of America, Bulletin, v. 79(9), p. 1097-1106.
- Brown, I.C., 1950. Fort Resolution, N.W.T., map and descriptive notes. Geological Survey of Canada, Paper 50-28.
- Brown, J.S. (ed.), 1967. Genesis of stratiform lead-zinc-barite-fluorite deposits. Economic Geology, Monograph no. 3, 443p.
- Brown, J.S., 1970. Mississippi Valley-type lead-zinc ores. A review and sequel to the "Behre Symposium". Mineral. Deposita (Berl.) v. 5, p. 103-119.
- Brown, P.A. and McEwan, J., 1982. Plutons as hosts? Geos, v. 11, (4), p. 12-15.
- Buchanan, T.J. and Somers, W.P., 1969. Discharge measurements at gaging stations. Chapter A8 in Book 3 of Techniques of Water-Resources Investigations of the United States Geological Survey. Washington, D.C.
- Budd, W.F., 1971. Derived physical characteristics of the Antarctic ice sheet. Meteorology Department, University of Melbourne, Publ. 18.
- Budd, W.F., Jenssen, D., and Radok, U., 1970. The extent of basal melting in Antarctica. Polarforschung, v. 6(39), p.293-306.
- Caine, T.W., Debicki, R.L., Goodwin, J.A., and Wilcox, A.F., 1981. 1981 index to mining assessment reports. Dept. of Indian and Northern Affairs, Canada, Ottawa, 531p.
- Calver, B., and Farnsworth, D.J.M., 1969. Open-pit dewatering at Pine Point Mines. Canadian Institute of Mining Met. Trans., v. 72, p. 341-347.

Brown, Erdman & Associates Ltd., 1981.
Western Mines Ltd., Great Slave Reef
Project, R-190 zone Aquifer Test
Analysis and Preliminary Dewatering
Design. Consulting Report.

Jonason, I.R., Jackson, L.E. and Sangster, D.F.,
1983. A Holocene zinc orebody formed by
superficial replacement of molasses. *J. Geom.
Explor.*, vol 18(3), p. 189-194

Lebedyanskaya, Z.P., 1982. Changes
in ground-water resources as a result
of mine drainage in the Severouralsk
bauxite area. in: *Unesco - Trans:
Studies and reports in hydrology*, vol. 34
(ground-water models, vol. 1), pp. 123-
130.

Medford, G.A., Maxwell, R.J. and Armstrong, R.L.,
1983. Sr-87/Sr-86 ratio measurements on
sulfides, carbonates, and fluid inclusions
from Pine Point, Northwest Territories,
Canada - an Sr-87/Sr-86 ratio increase
accompanying the mineralizing process.
Economic Geology, vol. 78(7), p. 1375-1378

Pine Point Mines, Ltd., 1983. License Renewal.
Application, Water Use License N123-0034.
Submitted to the N.W.T. - Water Board on
September 28, 1983.

Smith, N.G., Kyle, J.R. and Magara, K., 1983.
Geophysical log documentation of
fluid migration from compacting shales -
a universalization model from the
Devonian strata of the Pine Point Area,
Canada. Economic Geology, vol. 78(1),
p. 1364 - 1374.

Klunt

calite \rightarrow dolomite 6% like prob.

dolomite \rightarrow (calite)

dolomite very porous like
spongy; the porosity may
increase
like like shell, sized

Aggravation

W. & T. is remolded in 1000 years
million years

dolomite is replacement of calcite
by the carbonates precipitated
in cavities (in

Ca/P. ratio to help in water to determine

— for some replacement may cause
dissolution in porosity

10.72

14.22

34.00

28

Dedolomitization in feed water Canada
rest

Calox dissolves Ca carbonate
precipitate CaCO_3

Solubility of $\text{CaHCO}_3(\text{CO}_2)$ with increasing pressure

CaSO_4

Kazakhstan

Mg

Dedolomitization

2.7 kg
ppm

①

CO_2

②

dissolution of Dolomite

2.7 kg
2.7 Ca

5.27 HCO_3

12.0 kg from Dolomite

~~17.0 Ca~~

12.1 29.2

Dedob with stile

free since Canada signed

1981	1	2	3	4
1982	1	2	3	4
1983	1	2	3	4
1984	1	2	3	4
1989	1	2	3	4

800 USBP M =

4/sec

A-70

15 wells Sept 27, 28 / 1977

414 → 422

3 wells Sept. 29 ~~1977~~ Oct 2 / 1977

422 - 425

LIST OF MAJOR CHEMICAL CONSTITUENTS, IN PPM

SAMPLE NUMBER	CA	MG	NA	K	CL	SO4	HCO3
#19 414C	375.	179.	32.3	3.5	40.3	1390.	340.4
414-1C	380.	182.	32.3	3.3	40.3	1350.	352.6
#11 415C	383.	187.	36.2	3.4	48.0	1260.	352.6
415-1C	385.	187.	36.0	3.4	48.0	1250.	355.0
#13 416C	373.	168.	31.8	3.2	32.8	1370.	341.6
416-1C	368.	166.	31.8	3.2	32.8	1400.	347.7
#10 417C	378.	177.	105.	4.2	189.	1340.	337.9
#1 418C	372.	183.	32.8	3.5	63.	1500.	356.2
#2 419C	388.	190.	74.0	4.1	155.	1320.	350.1
#6 420C	417.	209.	168.	5.3	316.	1400.	351.4
#12 421C 1.0013	429.43	212.	308.	5.8	529.53	1398.14	337.5
#10 422C	420.	192.	131.	4.4	293.	1280.	324.5
#2 423C	400.	171.	31.3	3.3	45.5	1250.	329.4
#1 424C	409.	172.	31.5	3.3	40.8	1300.	324.5
#11 425C	418.	201.	146.	4.9	323.	1380.	337.9
425-1C	432.	208.	33.2	3.2	37.3	1280.	329.4
#17 426C	386.	166.	33.2	3.2	37.3	1280.	329.4
#15 427C	383.	167.	32.2	3.3	32.0	1330.	327.0
427-1C	385.	172.	33.5	3.4	32.0	1300.	345.3
#1 428C	375.	162.	30.3	3.2	30.6	1240.	362.3
428-1C	388.	171.	30.0	3.2	30.7	1370.	350.1
#19 433C	417.	180.	35.8	3.6	38.2	1540.	238.0
#20 434C	400.	177.	36.5	3.8	58.	1390.	276.9
#21 435C	390.	163.	36.0	3.6	40.6	1400.	278.1

711.3 3256 399.3 69.6 507.1 24362 521.7
 % 12 % 12 % 12 = % 12 % 12 = % 18 = % 12
 395.2 120.9 33.3 3.26 42.3 1353.7 307.5
 [19.72] [14.82] [1.45] [0.032] [1.19] [20.1] [5.07]

[YAGW L]

KAT:

19.72 + 14.82 = 34.54 = 0.032 - [5.152]
 1.19 + 22.12 = 23.31 = [34.74]

932
 % 7
 155.3
 [6.75]

1805
 % 6
 300.8
 [8.42]

34.74

LIST OF MAJOR CHEMICAL CONSTITUENTS, IN EPM

SAMPLE NUMBER	CA	MG	NA	K	CL	SO4	HCO3
414C	18.713	14.721	1.404	.090	1.136	28.940	5.579
414.1C	18.962	14.968	1.404	.084	1.136	28.107	5.779
415C	19.112	15.379	1.574	.087	1.354	26.233	5.779
415.1C	19.211	15.379	1.565	.087	1.354	26.233	5.818
416C	18.613	13.816	1.383	.082	.925	28.523	5.599
416.1C	18.363	13.652	1.383	.082	.925	29.148	5.699
417C	18.862	14.556	4.565	.107	5.330	27.899	5.538
418C	18.563	15.050	1.426	.090	1.777	31.230	5.838
419C	19.361	15.626	3.218	.105	4.371	27.482	5.738
420C	20.808	17.188	7.305	.136	8.911	29.148	5.759
421C	21.429	17.412	13.374	.148	14.927	29.110	5.531
422C	20.958	15.790	5.696	.113	8.263	26.650	5.319
423C	19.960	14.063	1.361	.084	1.283	26.025	5.399
424C	20.409	14.145	1.370	.084	1.151	27.066	5.319
425C	20.858	16.530	6.348	.125	9.109	28.732	5.538
425.1C	21.557	17.106	6.435	.130	9.109	28.107	5.899
426C	19.261	13.652	1.444	.082	1.052	26.650	5.399
427C	19.112	13.734	1.400	.084	.902	27.691	5.360
427.1C	19.211	14.145	1.457	.087	.902	27.066	5.659
428C	18.713	13.323	1.317	.082	.863	25.817	5.938
428.1C	19.361	14.063	1.304	.082	.866	28.523	5.738
433C	20.808	14.803	1.557	.092	1.077	32.063	3.901
434C	19.960	14.556	1.587	.097	1.636	28.940	4.538
435C	19.461	13.405	1.565	.092	1.145	29.148	4.558

J-69

ppw

1979

List of major chemical constituents
Sept. 20, 22, 23, 1979

	G	Na ₂	Na	K	Cl	So ₄	H ₂ O
395C #17	\365.	\133.	\21.9	\2.9	\19.3	\1130.	\320.9
396C #6	\360.	\132.	\21.3	\2.9	\18.0	\1130.	\320.9
396C #10	\360.	\135.	\21.2	\2.9	\18.0	\1150.	\316.0
397C #12	\375.	\134.	\22.2	\2.8	\20.4	\1150.	\324.5
398C #5	\383.	\137.	\23.2	\2.8	\21.8	\1250.	\294.0
399C #4	\322.	\117.	\19.1	\2.6	\16.3	\900.	\359.9
400C #10	\377.	\138.	\24.5	\3.3	\28.2	\1150.	\334.3
401C #14	\368.	\133.	\22.6	\2.8	\21.2	\1180.	\314.8
402C #3	\328.	\120.	\20.1	\2.6	\18.1	\920.	\347.7
403C #2	\335.	\126.	\20.5	\2.7	\18.5	\950.	\345.3
404C #1	\349.	\130.	\23.1	\2.8	\21.9	\1100.	\336.7
405C #12	\364.	\139.	\24.3	\2.9	\24.1	\1170.	\305.0
406C #11	\342.	\133.	\23.2	\3.0	\20.5	\1070.	\327.0
407C #15	\380.	\142.	\24.7	\3.0	\24.1	\1120.	\307.4
408C #10	\361.	\139.	\23.8	\3.0	\21.2	\1170.	\307.4
409C #20	\378.	\139.	\23.2	\3.0	\21.8	\1130.	\314.8
410C #16	\368.	\138.	\22.0	\3.0	\18.7	\1050.	\337.9

17-69

EPM

	Ca	Mg	Na	K	Cl	SO ₄	K ₂ CO ₃
395C	18.214	10.938	.952	.074	.544	23.527	5.260
396C	17.964	10.856	.926	.074	.508	23.527	5.260
396.1C	17.964	11.102	.922	.074	.508	23.943	5.179
397C	18.713	11.020	.965	.072	.575	23.943	5.319
398C	19.112	11.267	1.009	.072	.615	26.025	4.819
399C	16.068	9.622	.830	.067	.460	18.738	5.899
400C	18.812	11.349	1.065	.084	.795	23.943	5.479
401C	18.363	10.938	.983	.072	.598	24.568	5.160
402C	16.367	9.869	.874	.067	.510	19.154	5.699
403C	16.717	10.362	.891	.069	.522	19.779	5.659
404C	17.415	10.691	1.004	.072	.618	22.902	5.519
405C	18.164	11.431	1.057	.074	.680	24.359	4.999
406C	17.066	10.938	1.009	.077	.578	22.277	5.360
407C	18.962	11.678	1.074	.077	.680	23.318	5.038
408C	18.014	11.431	1.035	.077	.598	24.359	5.038
409C	18.862	11.431	1.009	.077	.615	23.527	5.160
410C	18.363	11.349	.957	.077	.527	21.861	5.538

R-61

ppm

1979

List of major chemical constituents,
in ppm Sep 20, 21, 1979

	Ca	Mg	Na	K	Cl	SO ₄	HCO ₃
386C #1	385.	139.	25.0	2.8	24.3	1320.	298.9
387C #7	407.	124.	19.8	2.7	16.3	1250.	305.0
388C #4	440.	125.	17.8	2.5	15.6	1230.	291.6
389C #10	400.	109.	15.0	2.3	10.6	1200.	317.2
390C #3	440.	131.	22.2	2.5	22.0	1400.	291.6
391C #12	430.	116.	16.9	2.2	14.3	1140.	302.6
392C #9	430.	135.	25.5	2.7	27.5	1250.	279.4
393C #5	439.	141.	27.6	2.7	30.3	1280.	274.5
394C	395.	136.	26.4	2.9	27.8	1200.	286.7
430C ^{Syn} (Sep 22)	428.	132.	22.8	2.8	22.3	1350.	305.0

R-61

1979

EDM

	Ca	Mg	Na	K	Cl	SO ₄	HCO ₃
386C	19.211	11.431	1.087	.072	.685	27.482	4.899
387C	20.309	10.198	.861	.069	.460	26.025	4.999
388C	21.956	10.280	.774	.064	.440	25.609	4.779
389C	19.960	8.964	.652	.059	.299	24.984	5.199
390C	21.956	10.773	.965	.064	.620	29.148	4.779
391C	21.457	9.540	.735	.056	.403	23.735	4.960
392C	21.457	11.102	1.109	.069	.775	26.025	4.579
393C	21.906	11.596	1.200	.069	.854	26.650	4.499
430C	21.357	10.856	.991	.072	.629	28.107	4.999
394C	19.711	11.185	1.148	.074	.784	24.984	4.699

ppm

S-65

A79 List of major chemical constituents
in ppm, Sept. 28, 1979

	Ca	Mg	Na	K	Cl	SO ₄	HCO ₃
429C #1	397.	113.	18.5	2.6	14.8	1100.	342.8

EDW

	Ca	Mg	Na	K	Cl	SO ₄	HCO ₃
429C	19.810	9.293	.804	.067	.417	22.902	5.618

SAMPLES FROM PIT W17, 1977

LIST OF MAJOR CHEMICAL CONSTITUENTS, IN PPM

SAMPLE NUMBER	CA	MG	NA	K	CL	SO4	HCO3
#2 86	220.	90.	16.	3.	13.	601.	417.
#3 85	190.	85.	10.	2.	7.	576.	396.
#5 109	290.	115.	17.	4.	10.	1004.	370.
#6 108	350.	150.	24.	5.	15.	1317.	368.
#7 88	350.	160.	27.	5.	17.	1259.	365.
#8 89	340.	160.	30.	5.	17.	1226.	378.
#9 107	330.	150.	30.	5.	17.	1284.	390.
#10 92	350.	145.	31.	5.	21.	1169.	403.
#11 99	350.	140.	30.	5.	33.	1160.	407.
#12 93	370.	145.	40.	5.	37.	1053.	410.
#13 100	520.	145.	700.	8.	1170.	1243.	394.
#14 96	320.	110.	100.	4.	14.	922.	427.
#15 101	220.	85.	10.	3.	14.	551.	419.
#16 95	320.	125.	23.	4.	18.	996.	429.
#17 97	400.	135.	230.	6.	370.	1136.	415.
#18 98	340.	135.	34.	5.	30.	1111.	412.
#19 59	300.	140.	24.	4.	16.	946.	418.
#20 75	280.	135.	28.	4.	14.	922.	428.
#21 94	310.	135.	24.	4.	14.	963.	424.
#22 90	320.	140.	30.	5.	17.	1160.	401.
#23 103	320.	135.	26.	4.	14.	1095.	406.
#24 104	370.	155.	25.	4.	14.	1358.	384.
#25 105	190.	90.	13.	2.	11.	700.	399.
#26 106	260.	95.	12.	3.	8.	782.	380.
#27 91	160.	75.	9.	2.	6.	461.	423.

W-17

1979

ppm

Lab of major chemical constituents in ppm
Sept. 29, 1979

		Ca	Mg	Na	K	Cl	SO ₄	HCO ₃
# 17	431C 1.0017	381.38	159.	569.570	6.4	1138.1140	1118.1120	398.2
# 14	432C 1.0013	375.	148.	434.435	5.7	839.840	1079.1080	415.5

in EDW

	Ca	Mg	Na	K	Cl	SO ₄	HCO ₃
431C	19.029	13.054	24.742	.163	32.093	23.279	6.527
432C	18.688	12.156	18.889	.146	23.657	22.456	6.809

Hagers Town Spring 1979

ppm

LIST OF MAJOR CHEMICAL CONSTITUENTS, IN PPM

SAMPLE NUMBER	CA	MG	NA	K	CL	SO4	HCO3
pool 367C June 6 1979	105.	20.5	5.8	1.7	5.0	212.5	129.3
Holbrook 372C Feb 5	495.	92.	9.3	1.3	11.6	1300.	257.4
pool 373C Feb 5	510.	90.	11.4	1.6	12.1	1300.	253.8
Holbrook 376C Feb 22	520.	81.5	21.3	1.9	22.0	1450.	287.
pool 377C Feb 22	525.	81.5	21.5	2.0	21.0	1420.	279.
Holbrook 381C Sep 17	529.	86.	17.6	1.7	21.0	1420.	279.4

EDW

367C	5.239	1.686	.252	.043	.141	4.424	2.119
372C	24.701	7.566	.404	.033	.327	27.066	4.219
373C	25.449	7.402	.496	.041	.341	27.066	4.160
376C	25.948	6.703	.926	.049	.620	30.189	4.704
377C	26.197	6.703	.935	.051	.592	29.564	4.573
381C	26.397	7.073	.765	.043	.592	29.564	4.579

Half way Spring

ppm

	Co	Mg	Na	K	Cl	Sa	lo ₂
368C JUL 16, 1979 pool near reservoir	503.	85.	22.5	2.0	21.0	1300.	294.
374C JUL 17, 1979 near, limestone pool	520.	83.	23.0	2.0	21.5	1550.	312.3
378C Aug 22, 1979 near limestone pool	525.	64.0	24.1	2.2	20.0	1270.	326.
382C Sep 17, 1979 near limestone pool	538.	72.	22.6	2.0	20.8	1200.	350.1

368C	25.100	6.990	.978	.051	.592	27.066	4.819
374C	25.948	6.826	1.000	.051	.606	32.271	5.119
378C	26.197	5.263	1.048	.056	.564	26.441	5.343
382C	26.846	5.921	.983	.051	.587	24.984	5.738

Salt Creek

1979

1 ppm

	Ca	Mg	Na	K	Cl	Sr	H ₂ O ₂
369C July 10/83	115.	63.	440.	2.6	660.	475.	113.2
375C July 10/83	198.	108.	840.	3.3	1110.	780.	164.7
379C Aug 22	582.	285.	3090.	11.0	5200.	2450.	160.
Stoppage of water intake was 3rd creek							
380C Aug 22	550.	264.	1950.	8.8	2400.	2170.	431.

383C Sept 17	635.640	295.377	2590.2610	9.910.0	3691.3700	2222.2040	233.7 235.5
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EPN

369C	5.738	5.181	19.131	.067	18.612	9.890	1.855
375C	9.880	8.882	36.523	.084	31.302	16.240	2.699
379C	29.042	23.438	134.353	.281	146.640	51.009	2.622
380C	27.445	21.711	84.786	.225	67.680	45.179	7.064
383C	31.686	24.234	112.593	.254	104.082	46.271	3.830

1979

Buffalo River

Little Buffalo River

Park Hk Creek

Sept. 24, 1979 + June 06

Sept 26, 1979

Sept 26, 1979

ppm

	Ca	Mg	Na	K	Cl	SO ₄	HCO ₃
411C BR	22.2	6.3	5.8	1.0	2.9	20.7	78.7
412C 60012	477.478	60.	419.420	2.3	589.592	1149.1150.	166.9 167.1
413C 60012	295.	160.	150.	4.0	265.	1050.	324.5

downstream of red bed with massive

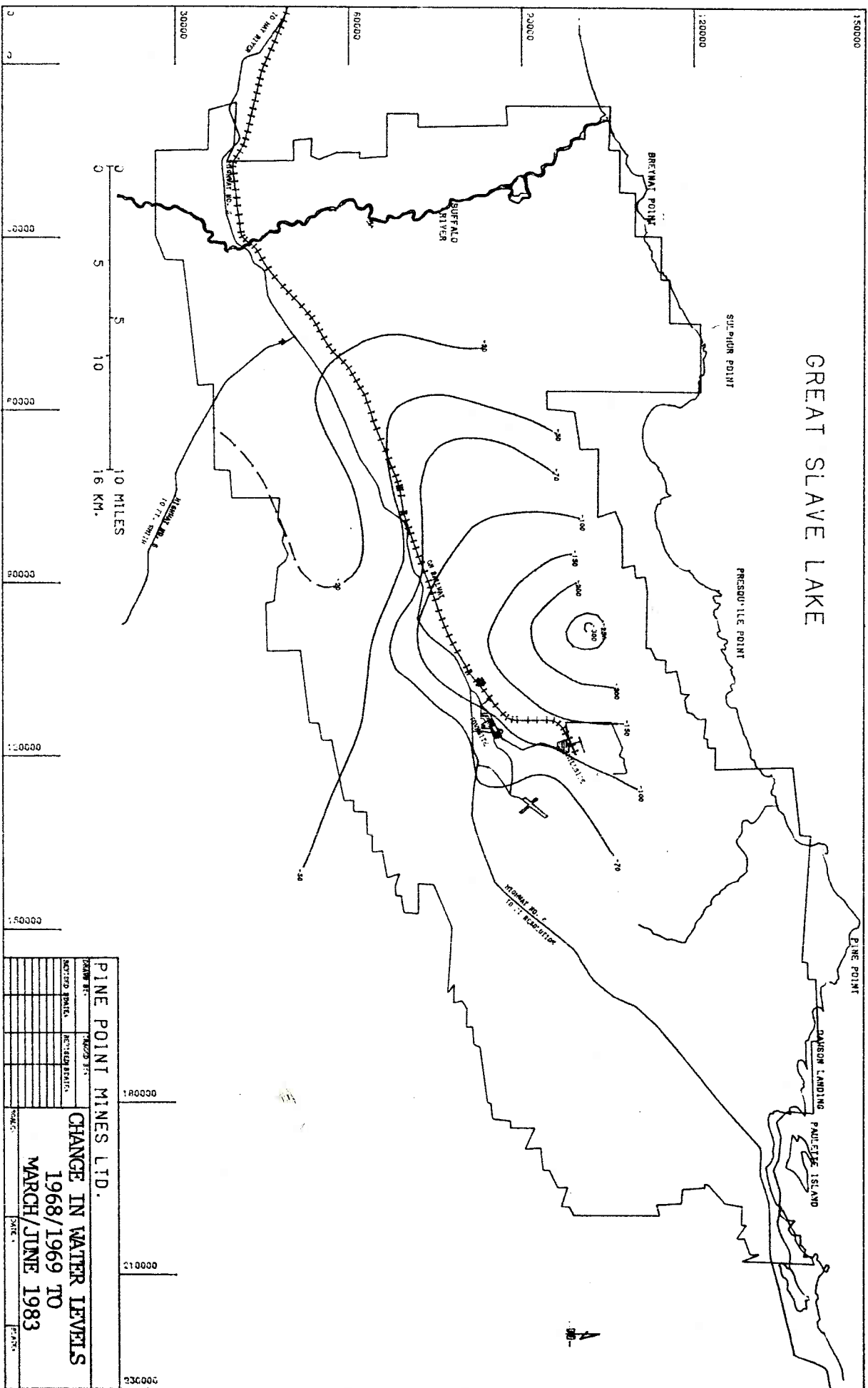
	Ca	Mg	Na	K	Cl	SO ₄	HCO ₃
370C 70012	49.	11.5	1.5	.65	1.8	25.	154.9
371C 70012	47.	11.1	1.2	.47	2.0	12.0	156.2

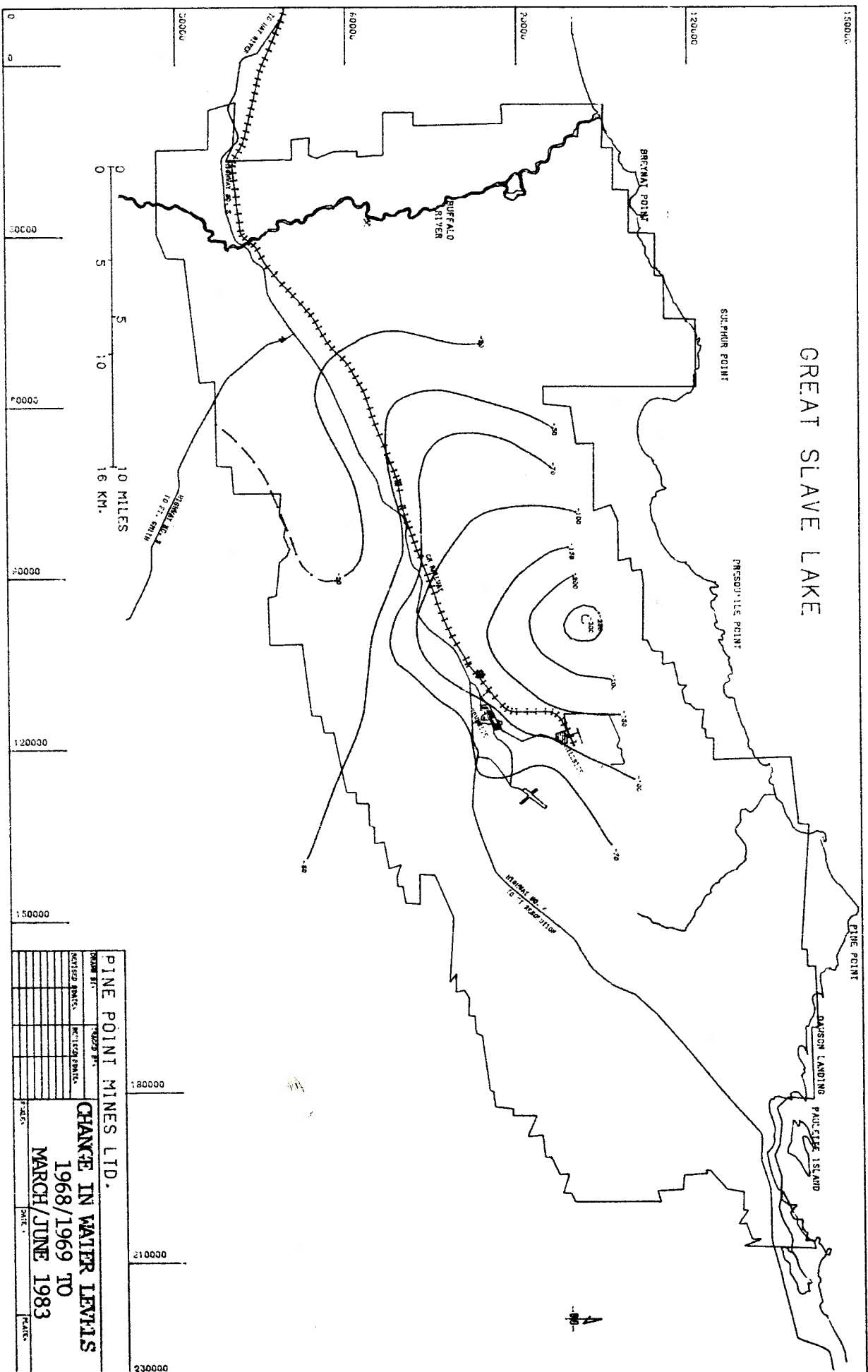
upstream of red bed with massive

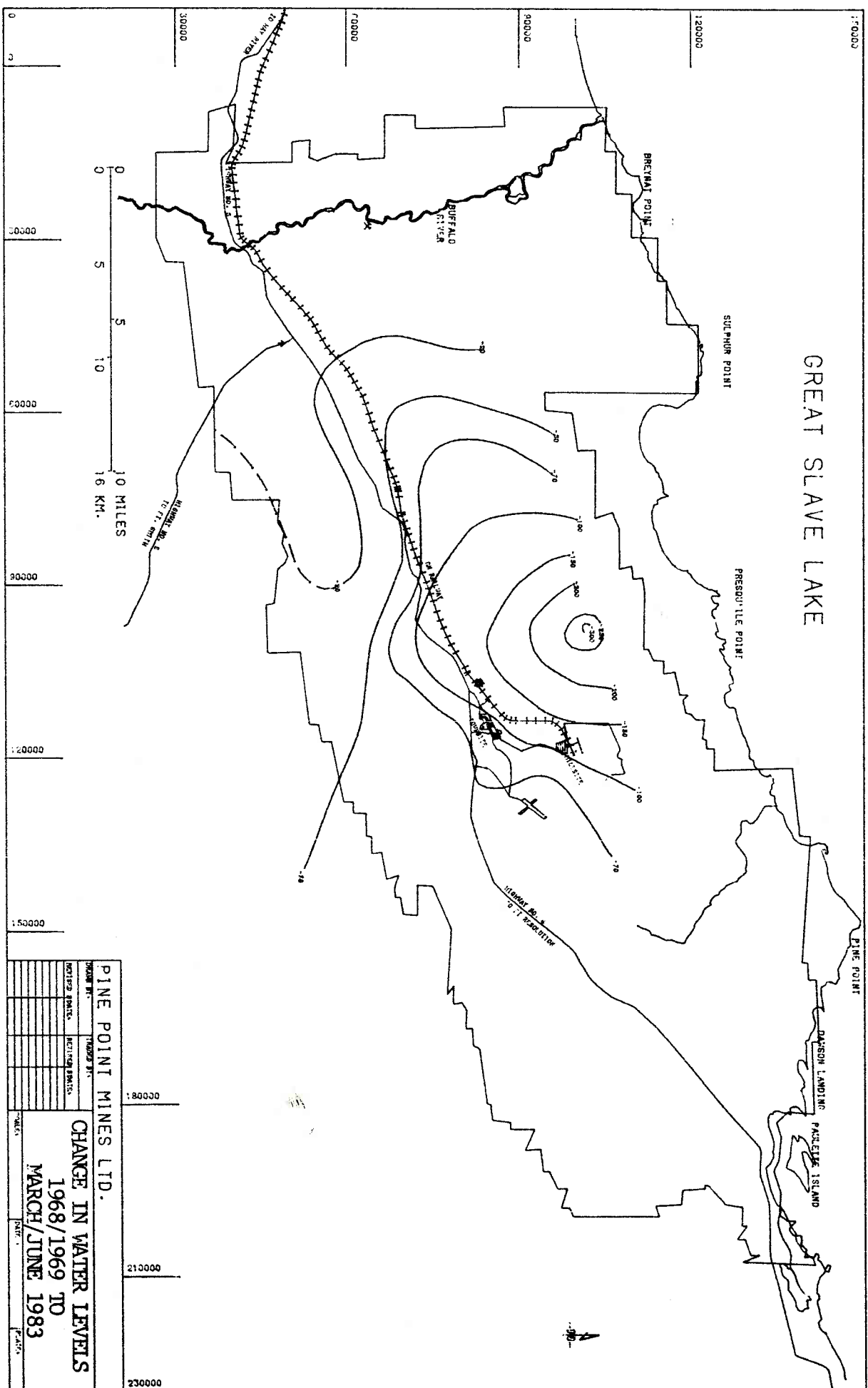
EPY

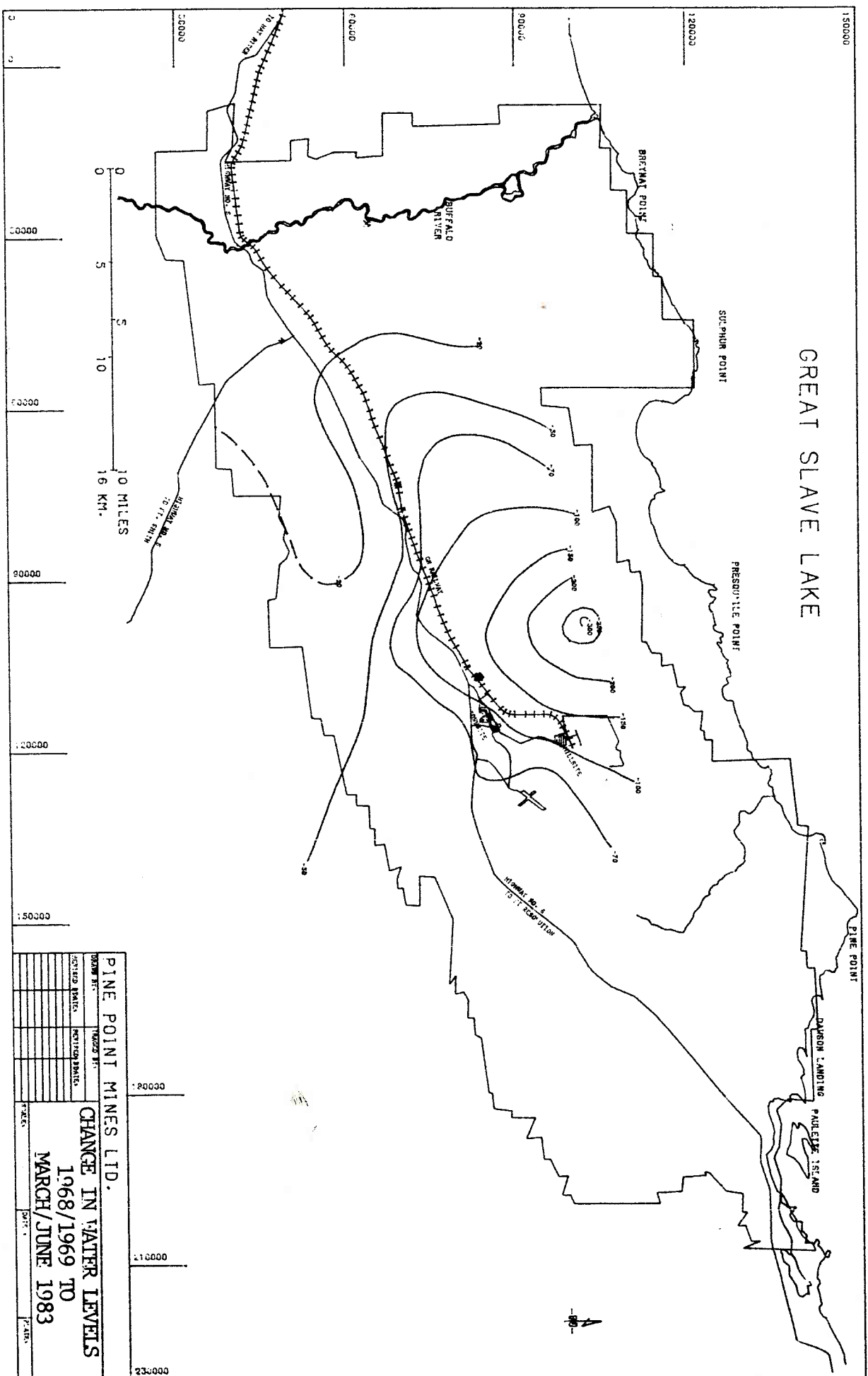
411C BR	1.108	.518	.252	.026	.082	.431	1.290
412C 60012	23.824	4.928	18.240	.059	16.618	23.914	2.735
413C 60012	14.720	13.158	6.522	.102	7.473	21.861	5.319

370C	2.445	.946	.065	.017	.051	.520	2.539
371C	2.345	.913	.052	.012	.056	.250	2.560









150000

GREAT SLAVE LAKE

120000

BREYNAI POINT

SULPHUR POINT

PRESCOTT POINT

PINE POINT

DAWSON LANDING PAULETTE ISLAND

SUFFALO RIVER

10 MI. RIVER

30000

60000

90000

0 5 10 15 20 MILES
0 5 10 15 20 KM.

10 MI. RIVER

30000

60000

90000

120000

150000

PINE POINT MINES LTD.

CHANGE IN WATER LEVELS
1968/1969 TO
MARCH/JUNE 1983

DATE

DATE

DATE

DATE

DATE

DATE

DATE

DATE

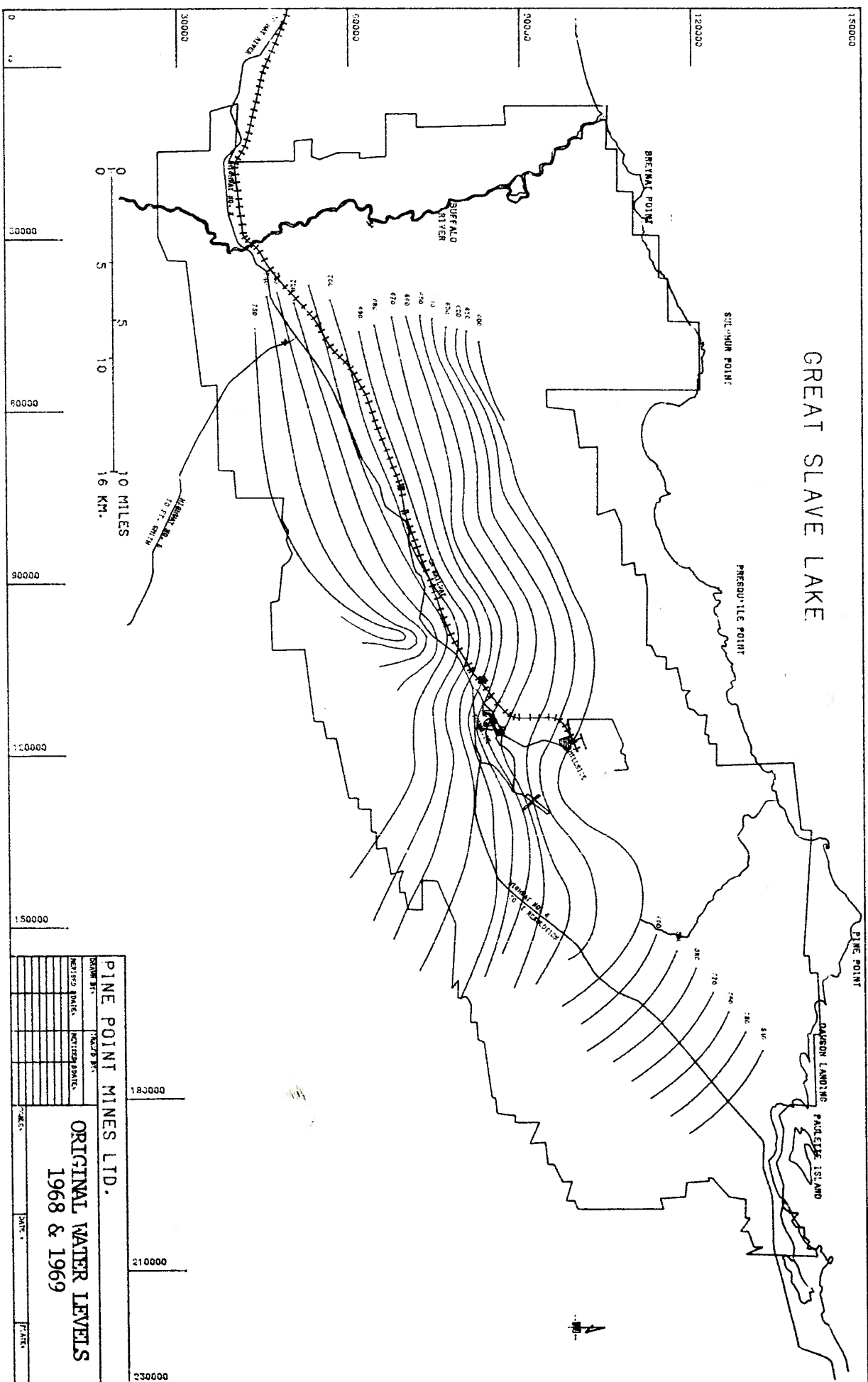
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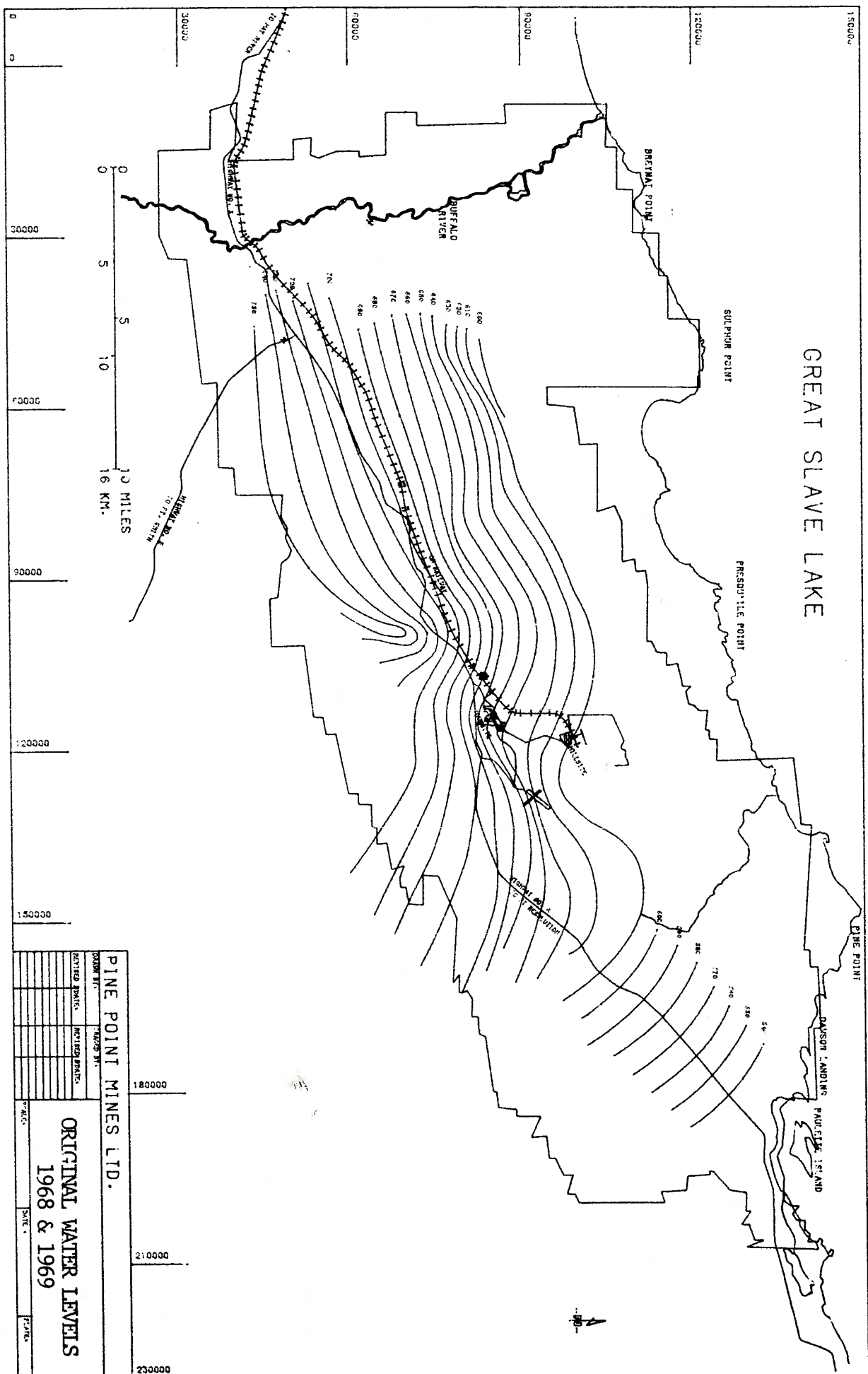
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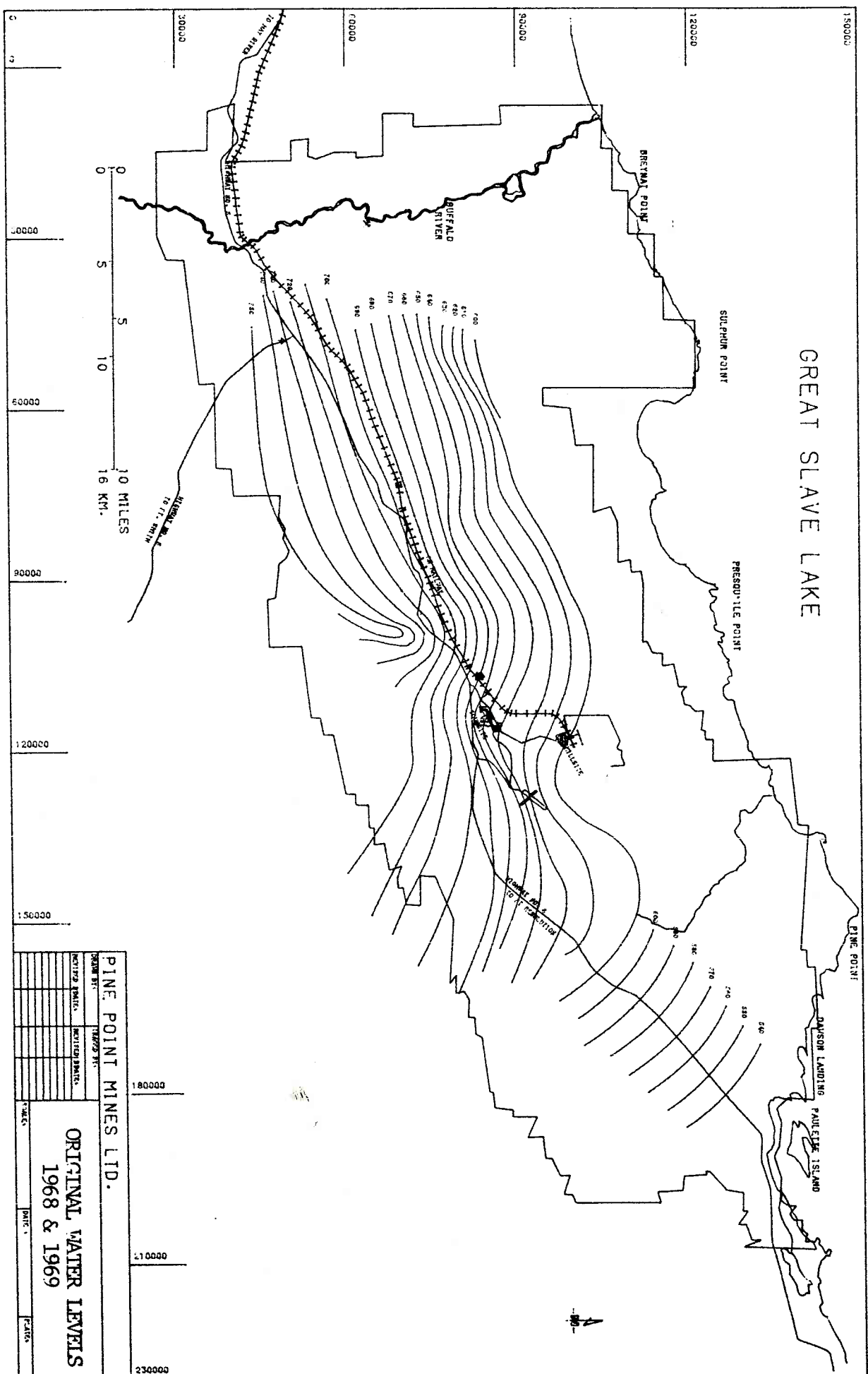
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150000

GREAT SLAVE LAKE

120000

90000

70000

30000

PINE POINT

DAWSON LAKE AND PAULISSE ISLAND

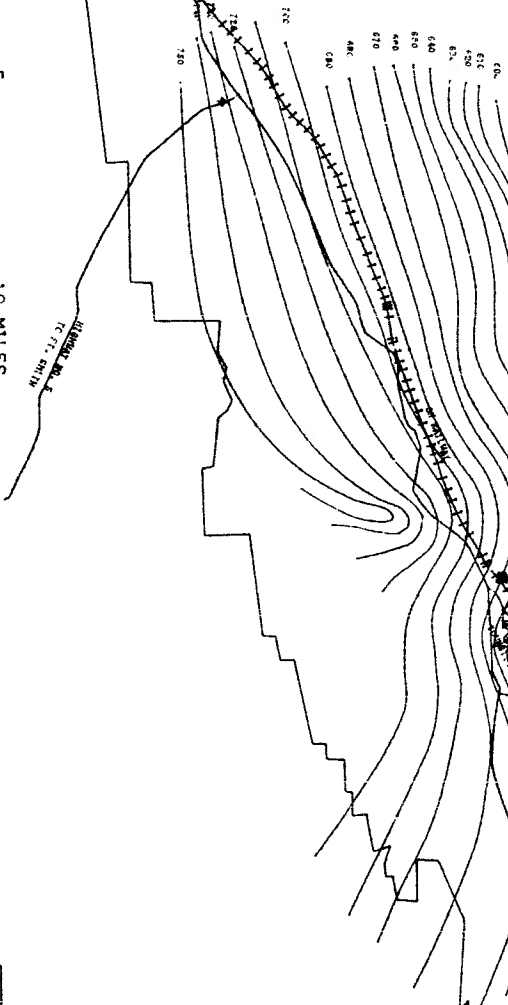
SULPHUR POINT

PRESCOTT POINT

BREYNA POINT

BUFFALO RIVER

0 5 10 16 KM.
0 5 10 MILES



PINE POINT MINES LTD.

ORIGINAL WATER LEVELS
1968 & 1969

DATE	TIME	LOCATION	WATER LEVEL (FT.)
1968			
1969			

