Bulletin 38

The Hydrogeology of the Athabasca Oil Sands Area, Alberta

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Alberta
RESEARCH COUNCIL

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ABSTRACT

The area of study includes most of the Athabasca Oil Sands deposit and extends from Tp 77 to Tp 100, and R1 to 25 west of the fourth meridian: a total of about 67,260 km^2 (25,970 sq. mi). Holocene and Cretaceous clastic rocks unconformably overlie Devonian nonclastic rocks resting on Precambrian basement. Regional dip is toward the southwest. A major fault passing north-northwestward under Fort McMurray is hypothesized, with a downthrow west of about 273 ft (83 m); it appears to be of post-Devonian age. Partial solution of Prairie Evaporite Formation salts extends about 16 km (10 mi) west of the fault; to the east solution is almost complete. Collapse features are particularly notable at the Cretaceous-Devonian contact.

West of the fault three hydrostratigraphic units are defined:

1) The K-Q hydrostratigraphic unit, consisting of Holocene and Cretaceous sediments, is characterized by alternating vertical and horizontal groundwater flow controlled by zones of low and high hydraulic conductivity, respectively. Unsaturated zones extend up to 10 km (6 mi) from outcrop into the units of high hydraulic conductivity. Total dissolved solids contents in groundwaters are usually less than 10,000 mg/L and commonly less than 5000 mg/L.

2 The D-2 hydrostratigraphic unit, consisting essentially of Upper Devonian strata, has dominantly horizontal groundwater flow towards a zone of hydraulic heads located roughly coincident with the fault at elevations generally equal to those of the Athabasca River. Total dissolved solids concentrations are usually less than 40,000 mg/L, but are higher to the southwest and in the north-center of the area.

3) The D-1 hydrostratigraphic unit, consisting of the Methy, McLean River, and La Loche Formations that underlie the Elk Point evaporites, has horizontal groundwater flow toward the fault zone. Freshwater hydraulic heads west of the fault are approximately at land surface, but decline eastward to the elevations of major rivers. Total dissolved solids concentrations exceed 200,000 mg/L west of the fault.

The D-1 and D-2 hydrostratigraphic units merge east of the fault. Groundwater flows west towards the fault, with total dissolved solids concentrations seldom exceeding 50,000 mg/L.

On a regional basis, the oil sands have a finite hydraulic conductivity commonly of 10^{-6} to 10^{-4} cm/sec.

Surface mining ventures will generally require that the oil sands and underlying aquifers be depressurized. Hydrogeological conditions will affect depressurization:

1) pumping volumes will vary widely;
2) in produced water total dissolved solids may range up to 300,000 mg/L;
3) hydrogen sulfide gas contents will vary greatly;
4) induced infiltration from the Beaverhill Lake Formation or the Athabasca River may occur;
5) collapse features and faults caused by evaporite solution may have affected the oil sands sufficiently that loss of pressures and fluids could occur in in situ operations.

Structural conditions are suitable for injection of waste liquids into the D-2 hydrostratigraphic unit only west of the limits of evaporite solution. Waste injection into the Beaverhill Lake Formation may be possible where the overlying Woodbend Group is sufficiently thick.

INTRODUCTION

PURPOSE

The Alberta Research Council began a regional hydrogeological evaluation of the Athabasca Oil Sands area in 1973. The area under study includes most of the Athabasca Oil Sands deposit (Fig. 1) and encompasses the area from Tps 77 through 100 and Rs 1 through 25 west of the fourth meridian. (Unless otherwise noted, all land locations in this report are west of the fourth meridian.) This is an area of about 67,260 km^2 (25,970 mi^2).

The Athabasca Oil Sands ranks one of the major hydrocarbon accumulations of the world. Estimates (Outtrim and Evans, 1977) place the amount of bitumen in the deposit of 138.1 x 10^9 m^3 (868.7 x 10^9 BBLS). Great Canadian Oil Sands (now Suncor, Inc.) has surface mined the deposit since 1967, and mining will commence soon at the Syncrude site. Both of these operations have encountered unexpected groundwater problems. The existence of these problems and the possibility of others led to this regional hydrogeological investigation.

The philosophy behind this project is that an early understanding of the groundwater conditions of the area will allow consideration of potential environmental and technical problems related to using the resource. The ultimate goal of the project is an understanding of the regional hydrogeology of the area. The purpose of this publication is to present a conceptual model of the geology and groundwater regime.

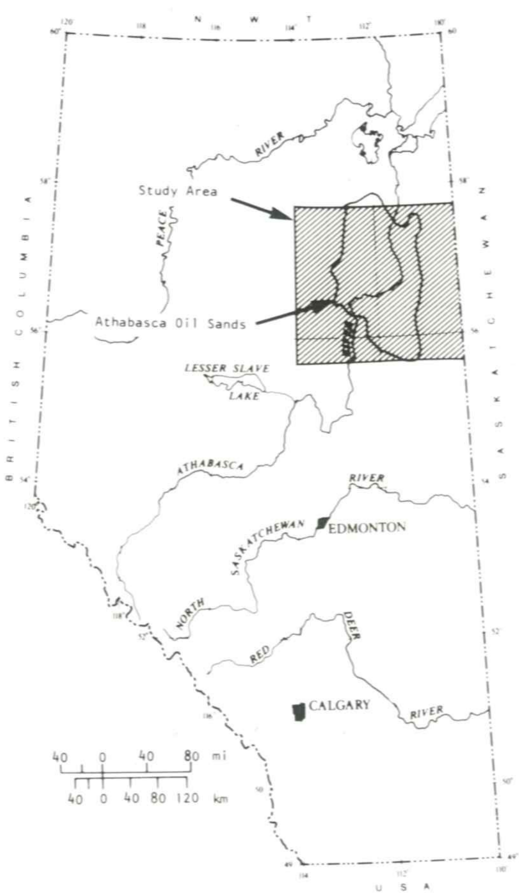


FIGURE 1. Location of the Athabasca Oil Sands Area

A regional observation well network was installed during the winters of 1974-75 and 1975-76. Seventy-five observation wells up to 581 m (1905 ft) deep (Appendix 1) were installed at 15 locations (Fig. 2) within the study area. Separate wells of various depths were constructed at each location so that the vertical variation of groundwater parameters could be sampled. Basic data on this network, including site geology, well construction details, aquifer test results, water analyses, and water level hydrographs has been published (Hackbarth, 1976; 1977; Brulotte and Hackbarth, in press).

The reader is referred to these publications for specific information regarding the network.

ACKNOWLEDGMENTS

The project was funded by Alberta Energy and Natural Resources, with supervision of activities carried out by a joint Energy and Natural Resources - Research Council management committee.

Technical staff included M. E. Brulotte, G. M. Jean, K. Holmes, D. G. Sjostrom, and M. Walls who, through hard work during long hours particularly during the field season, accomplished much in the short time available. R. A. Lailey, of Bomay Oilfield Services Ltd., assisted in the planning and construction of the wells. His efforts are greatly appreciated.

The following companies permitted the use of groundwater observation wells that had already been installed: BP Oil and Gas Ltd., Home Oil Company Ltd., Petrofina Canada Ltd., Shell Canada Ltd., and Tenneco Oil and Mineral Ltd. (Appendix 1; Fig. 2). Other companies cooperated by providing information on lease access.

Alberta Oil Sands Environmental Research Program (AOSERP) made its facilities available to personnel working on this project.

One observation well site is located within the Forest Service Yard in Fort McMurray. The cooperation of L. Babcock, Athabasca Forest Superintendent, in allowing these wells to be drilled is appreciated.

F. W. Schwartz of the Geology Department, University of Alberta, critically reviewed and commented on the manuscript.

The manuscript was reviewed in depth by R. Green and B. Hitchon of Alberta Research Council. G. D. Mossop and D. A. Redford, both with Alberta Research Council, and R. Gerard, Civil Engineering Department, University of Alberta, examined the sections on geology, in-situ recovery, and surface water hydrology, respectively. Their comments and criticism are appreciated.

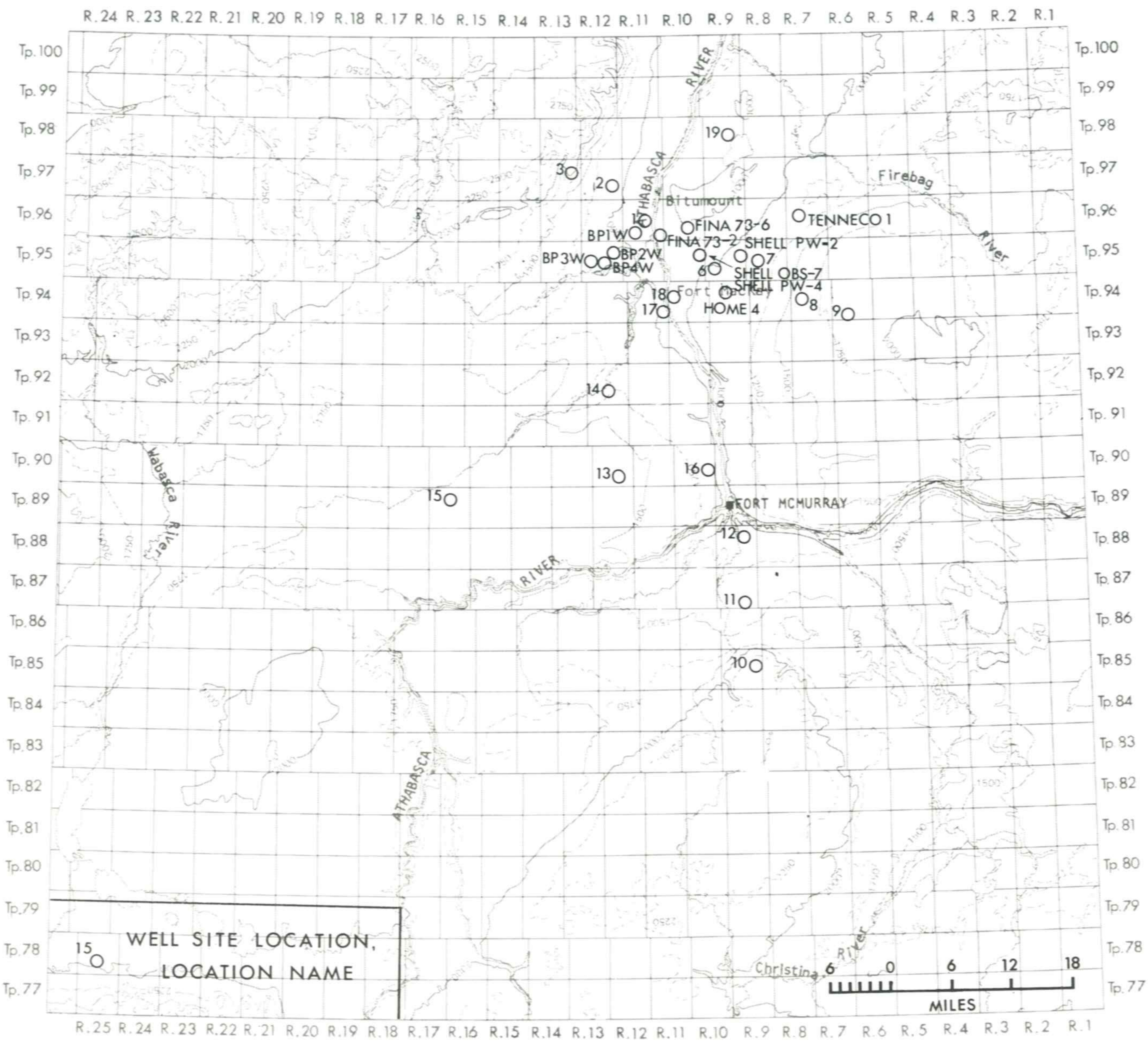


FIGURE 2. Location of observation wells

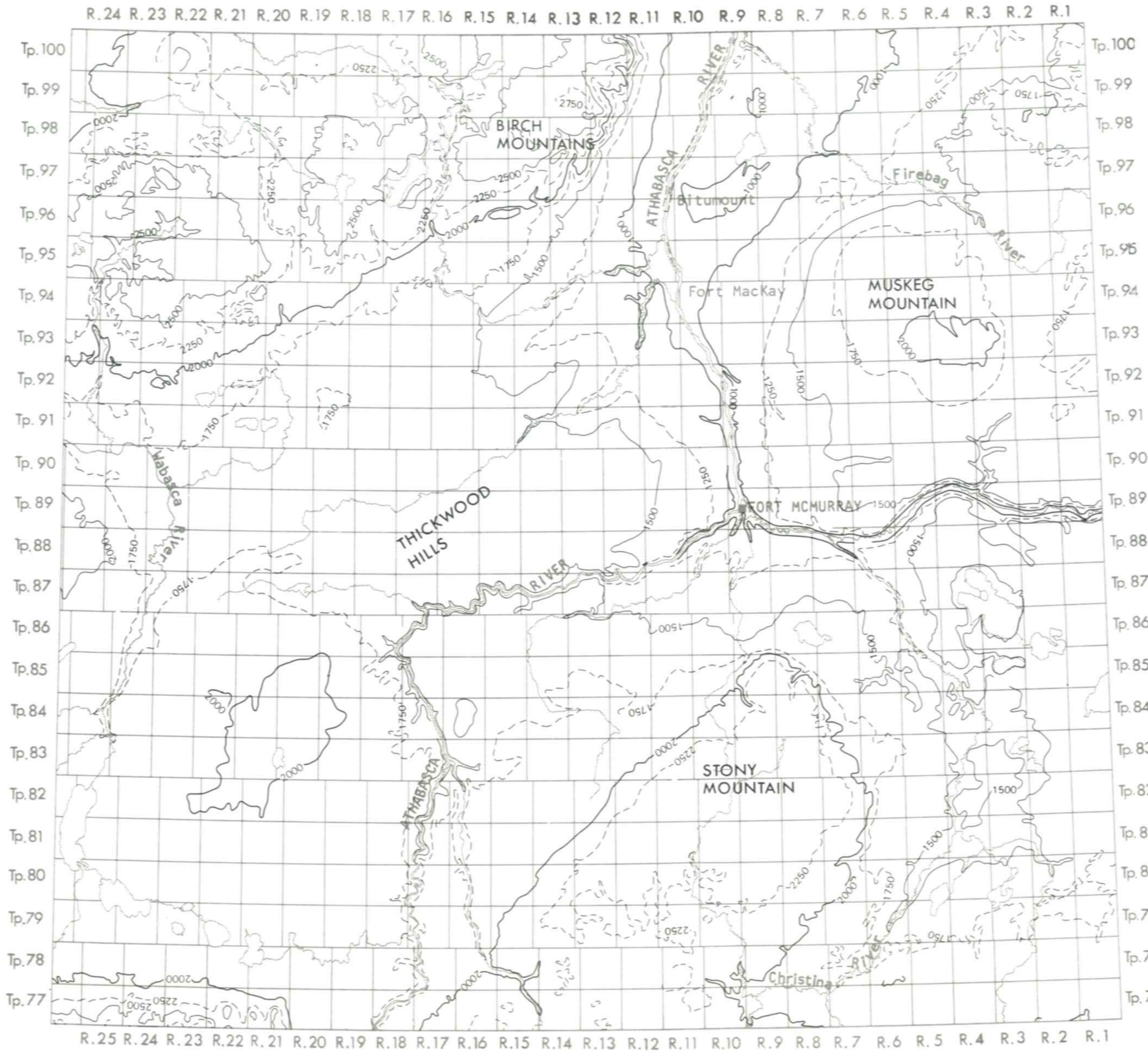


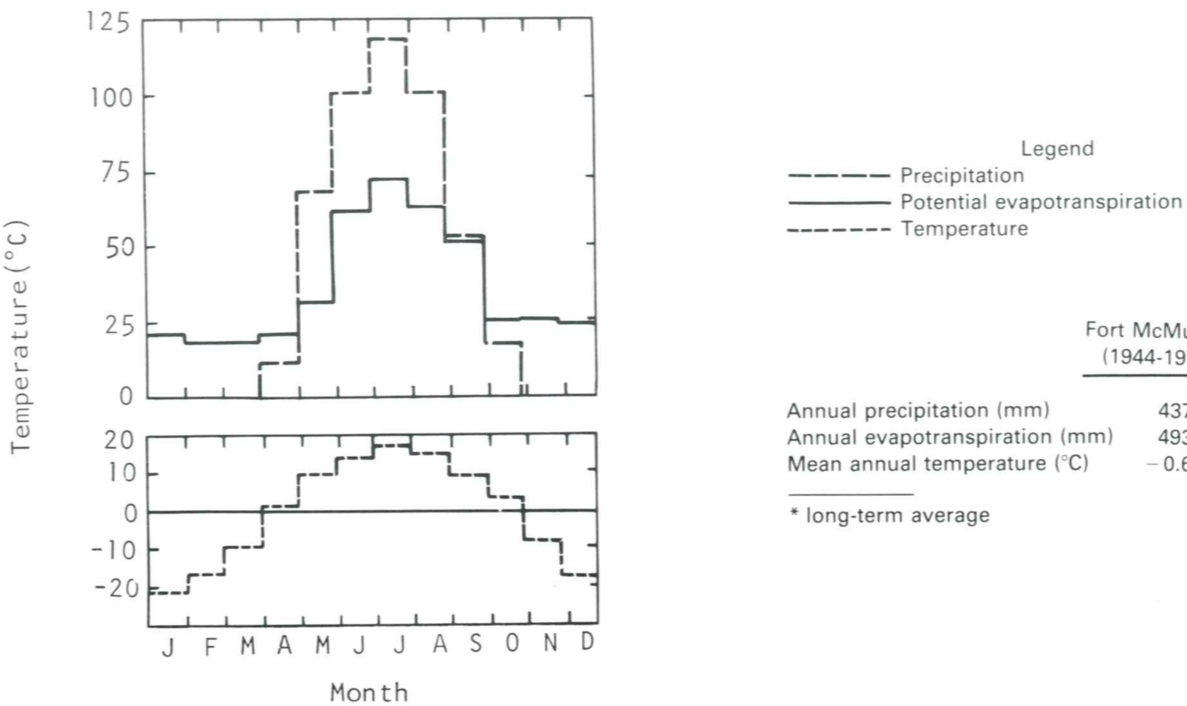
FIGURE 3. Topography, drainage, and physiographic features

PHYSIOGRAPHY

The Athabasca Oil Sands area lies within two major physiographic regions — the Canadian Shield and the Interior Plains (Fig. 3). Only the far northeast corner is in the Shield. Within the Plains portion of the area are four major uplands: the Birch Mountains, with elevations up to 2700 ft (823 m); Muskeg Mountain, with elevations up to 2000 ft (610 m); Stony Mountain which rises to 2500 ft (762 m); and the Thickwood Hills with elevations exceeding 1700 ft (518 m).

Between these uplands is a broad flat plain which slopes gradually towards the major streams and rivers (Fig. 3). The Athabasca and Clearwater Rivers are incised several hundred feet into this plain. The hydraulic grade lines of minor tributaries (other than the Clearwater River) to the Athabasca River drop quite rapidly within a few miles of the river, producing precipitous gorges. Farther upstream these tributaries are generally slow flowing and meandering.

About 50 percent of the area is covered by organic soil (Lindsay *et al.,* 1958, 1962, 1963) referred to as muskeg. Muskeg is present on both the uplands and the gently sloping plains. The actual slope of the land surface seems to determine whether or not muskeg is present, because muskeg is uncommon on steep slopes but is quite prevalent on flat to moderately steep slopes. Frost has been noted during the summer within the muskegs in the northwest quarter of the area (Lindsay *et. al.,* 1958, 1962, 1963). Whether this is permafrost or climafrost is not known.



	Fort McMurray (1944-1972)
Annual precipitation (mm)	437*
Annual evapotranspiration (mm)	493*
Mean annual temperature (°C)	−0.6*

* long-term average

FIGURE 4. Mean monthly precipitation, evapotranspiration, and temperature at Fort McMurray Airport, 1944-1972

CLIMATE

The climate is characterized by long cold winters and short cool summers (Fig. 4). January temperatures at Fort McMurray average about -22°C (-7°F), July temperatures average 16°C (61°F) (A. Mann, Environment Canada, pers. comm.), and the mean annual temperature is -0.6°C (31°F).

There are usually fewer than 100 frost-free days per year (Longley, 1968). The first frost usually occurs in the Athabasca River Valley between August 15 and 31 and in the uplands between September 1 and 15.

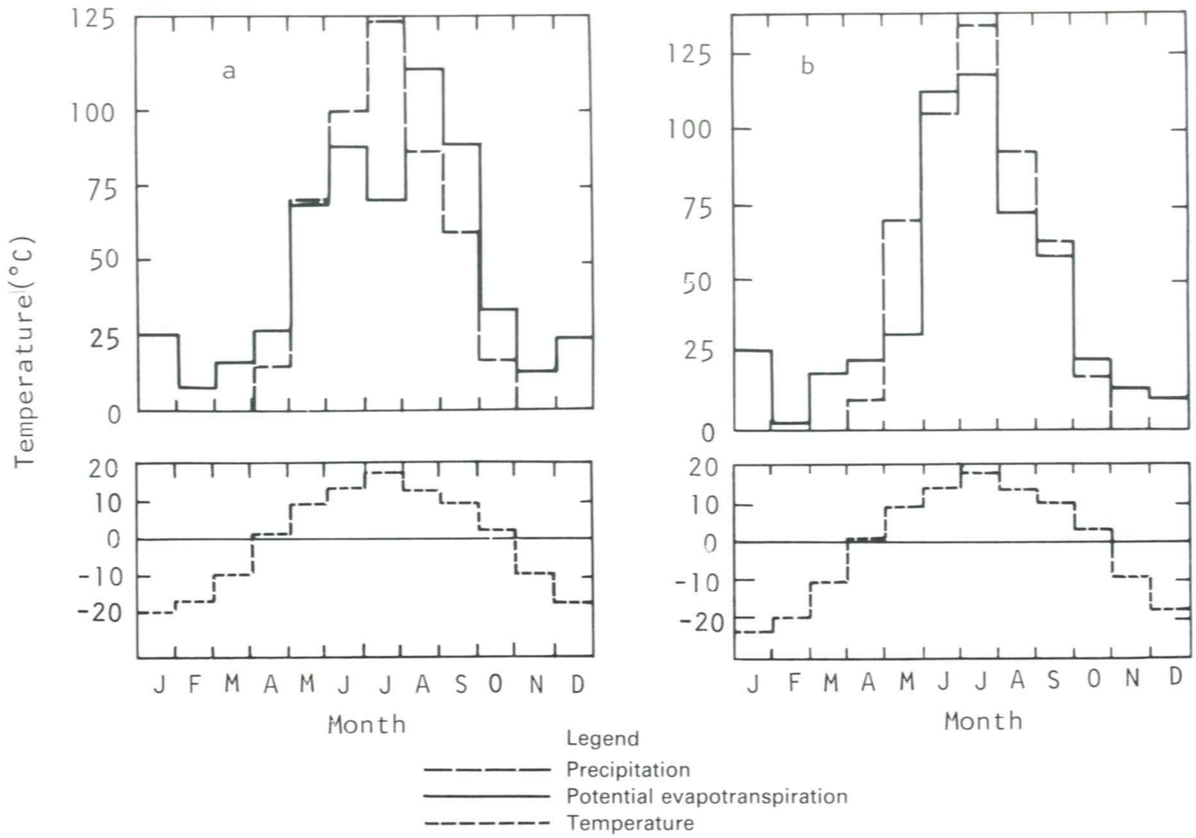
The average annual precipitation at Fort McMurray Airport is about 437 mm (17 in), slightly over half of which falls as rain during June, July, August, and September (Fig. 4). Snowfall averages about 1500 mm (59 in) each year and is quite evenly distributed among the winter months.

The prevailing wind direction at Fort McMurray Airport is from the west (Longley, 1968). Wind patterns may be significantly different within the river valley.

Bruce and Weisman (1967) showed that annual evaporation is likely about 381 to 508 mm (15 to 20 in). Potential evapotranspiration, as calculated by the method of Thornthwaite and Mather (1957), is about 493 mm (19 in) per year — which should be regarded as a maximum value because the tables of unadjusted daily potential evapotranspiration do not contain "heat index" values low enough for the study area. However, the error in the potential evapotranspiration value should not be greater than about 50 mm (2 in) because the values of unadjusted potential evapotranspiration are fairly insensitive to small changes in the "heat index". Monthly potential evapotranspiration exceeds the average monthly precipitation at Fort McMurray Airport from May through August (Fig. 4), and annual potential evaporation exceeds average annual precipitation.

A weather station was established at Mildred Lake (Tp 92, R 10) and collection of data began in 1973. The data for 1975 for Mildred Lake and Fort McMurray Airport are presented (Fig. 5) to give some indication of the meteorological conditions during the study.

Weather conditions during 1975 were considerably different from normal at Fort McMurray Airport in that precipitation exceeded the long-term average and also exceeded potential evapotranspiration. Similar conditions presumably prevailed at Mildred Lake, although there is insufficient data for calculation of mean values. Total precipitation in 1975 (Fig. 5) was about 76 mm (3 in) less and the mean annual temperature about 0.8°C (1.4°F) lower at Mildred Lake than at Fort McMurray. The lower average temperature at Mildred Lake is due to its location within the Athabasca River Valley. Cold air tends to accumulate in the river valley during winter, so the monthly average temperatures for November through April 1975 are lower at Mildred Lake than at Fort McMurray Airport. However, summer temperatures were slightly warmer at Mildred Lake than at Fort McMurray Airport.



	Fort McMurray (1975)	Mildred Lake (1975)
Annual precipitation (mm)	596	520
Annual evapotranspiration (mm)	499	499
Mean annual temperature (°C)	−0.1	−0.9

FIGURE 5. Mean monthly precipitation, evapotranspiration, and temperature at (a) Fort McMurray Airport and (b) Mildred Lake, 1975

SURFACE WATER HYDROLOGY

Two gauging stations, located at Fort McMurray (Tp 90, R 9) and Embarras (Tp 106, R 9), monitor flow in the Athabasca River within or near the study area (Environment Canada, 1974; 1975; 1976). As of 1976 all major tributaries to the Athabasca River between Fort McMurray and Embarras had been instrumented and it is interesting to note that 75 percent of the 3.3 x 10^8 m^3 of gain in annual flow between these two stations could be accounted for from these streams (Loeppky and Spitzer, 1977). During baseflow conditions of December 1976 (Table 1) this same percentage of the estimated gain in discharge between Fort McMurray and Embarras (18.4 m^3/sec) was accounted for by the tributaries (13.7 m^3/sec). It thus appears that about 25 percent of the gain in flow between Fort McMurray and Embarras (or roughly 2 percent of the flow at Fort McMurray) is due to groundwater entering the channel of the Athabasca River; however, 2 percent of total flow is smaller than the usual accuracy of 5 percent claimed for stream gauging measurements (R. Gerard, University of Alberta, pers. comm.). As well, the channel at Embarras may shift suddenly in a random direction (M. Spitzer, Water Survey of Canada, pers. comm.) so measurements at that station are subject to additional small errors. Thus it is not possible to state positively that groundwater is contributing to the flow in this reach of the Athabasca River; in any event, the amount, in terms of total flow, is negligible.

Also given in table 1 are total dissolved solids concentrations and chloride iron concentrations for waters in various streams. These values are for "grab" samples, not samples composited from across the entire flowing section of the river. In a large river mixing of incoming tributary waters may be slow, so the values for the Athabasca River may be somewhat in error.

During baseflow conditions in December 1976, chloride ion concentration in the Athabasca River increased from 5 mg/L at Horse River to 19 mg/L just north of Fort McMurray (Table 1). The Clearwater River, at the same time, had a

TABLE 1
Total dissolved solids, chloride ion content and mean monthly flow of streams during baseflow conditions

Stream	Location (W 4th)	TDS (mg/L)	Chloride (mg/L)	Flow m^3/sec	Date
Hangingstone	32-85-9	300	4	-	10/1/76
Hangingstone	10-89-9	380	34	0.4	10/1/76
Unnamed	2-87-9	864	4	-	10/1/76
Unnamed	26-87-9	444	54	-	10/1/76
Saprae	32-88-8	332	4	-	8/1/76
Prairie	23-88-9	434	76	-	8/1/76
Saline	10-89-9	470	8	-	8/1/76
Horse	8-89-9	353	15	0.4	10/1/76
Conn	35-89-11	208	4	-	8/1/76
Conn	31-89-10	346	4	-	8/1/76
Conn	23-89-10	436	4	-	8/1/76
Conn	29-89-9	670	4	-	10/1/76
Steepbank*	29-92-9	342	7	0.4	12/2/76
Dunkirk	31-90-19	279	4	0.1	12/2/76
MacKay	4-90-16	664	8	-	18/1/76
MacKay*	24-94-11	424	42	0.6	25/2/76
Muskeg	24-95-10	330	6	-	24/2/76
Muskeg*	29-94-10	316	6	0.4	24/2/76
Ells*	8-95-11	120	14	1.4	24/2/76
Joslyn	29-95-11	476	10	0.0	24/2/76
Tar*	29-96-11	352	12	0(est)	24/2/75
Pierre*	30-97-10	352	12	0(est)	16/3/75
Calumet*	11-97-11	846	96	0(est)	16/3/75
Eymundson	10-98-9	656	12	0(est)	16/3/75
Firebag*(1)	36-99-8	268	7	10.9	12/76
Poplar*	24-91-10	-	-	0.0	2/76
Beaver*	26-93-11	-	-	0.0	2/76
Clearwater	32-88-8	84	37	69.0	10/12/76
Athabasca					
a) at Horse River	17-89-9	226	5	-	10/12/76
b) downstream of Fort McMurray	5-90-9	161	19	188.3	10/12/76
c) 156 km north of Fort McMurray	104-9	116	30	-	11/12/76
d) Embarras, 192 km north of Fort McMurray	106-9	-	-	206.7(E)	12/76

*Tributary to Athabasca River below Fort McMurray; total flow rate 13.7 m^3/sec

(E)December 1976 flow at Embarras is not available - the value given constitutes the average of the ratios of the December flow at Embarras to that at Fort McMurray (1971-1975) times the December 1976 flow at Fort McMurray.

(1)Total dissolved solids and chloride ion are from sample taken February 11, 1976

Flow - average for the month of the water sample

Source: a) Loeppky and Spitzer (1977)
b) M. Spitzer, Water Survey of Canada, (pers. comm.)
c) R. Froelich, AOSERP, (pers. comm.)

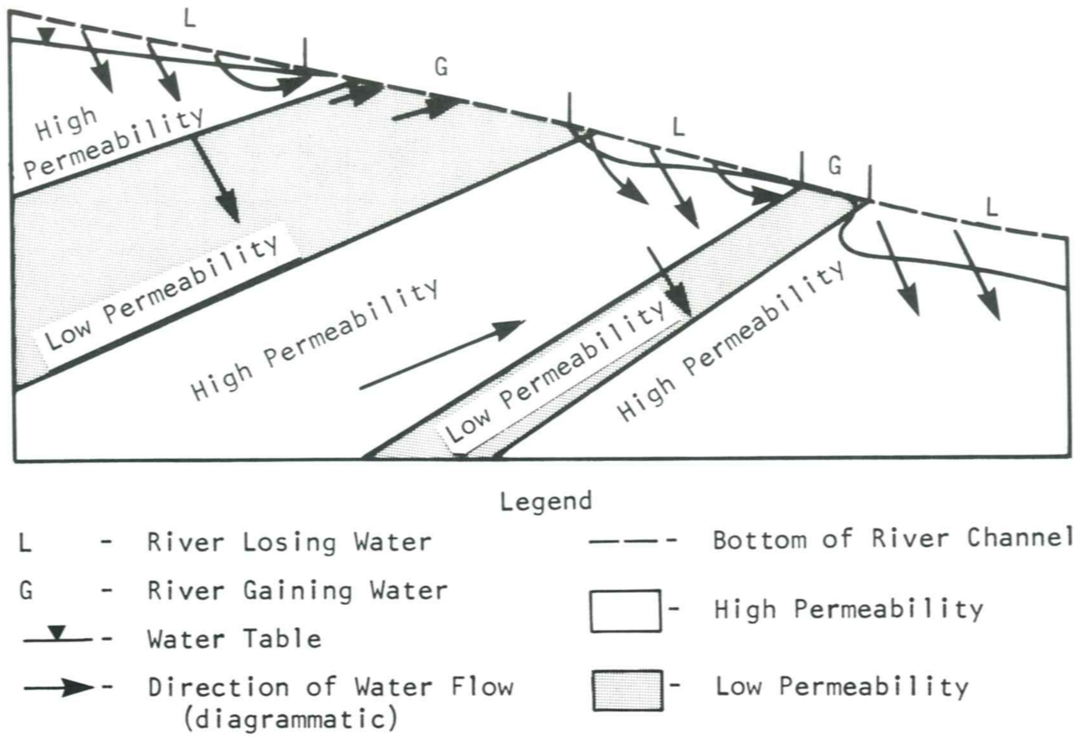


FIGURE 6. Diagrammatic cross section along a river draining the Birch Mountains

chloride ion concentration of 37 mg/L and a flow equivalent to 60 percent of the discharge of the Athabasca River. A simple, complete mixing of these two rivers would put concentrations in the Athabasca River below Fort McMurray at about 17 mg/L and the sample (Table 1) is consistent with this model. The difference (2 mg/L) could be due to the discharge from the Fort McMurray sewage treatment plant or due to sampling of incompletely mixed waters. A similar calculation for total dissolved solids concentrations gives equally consistent results.

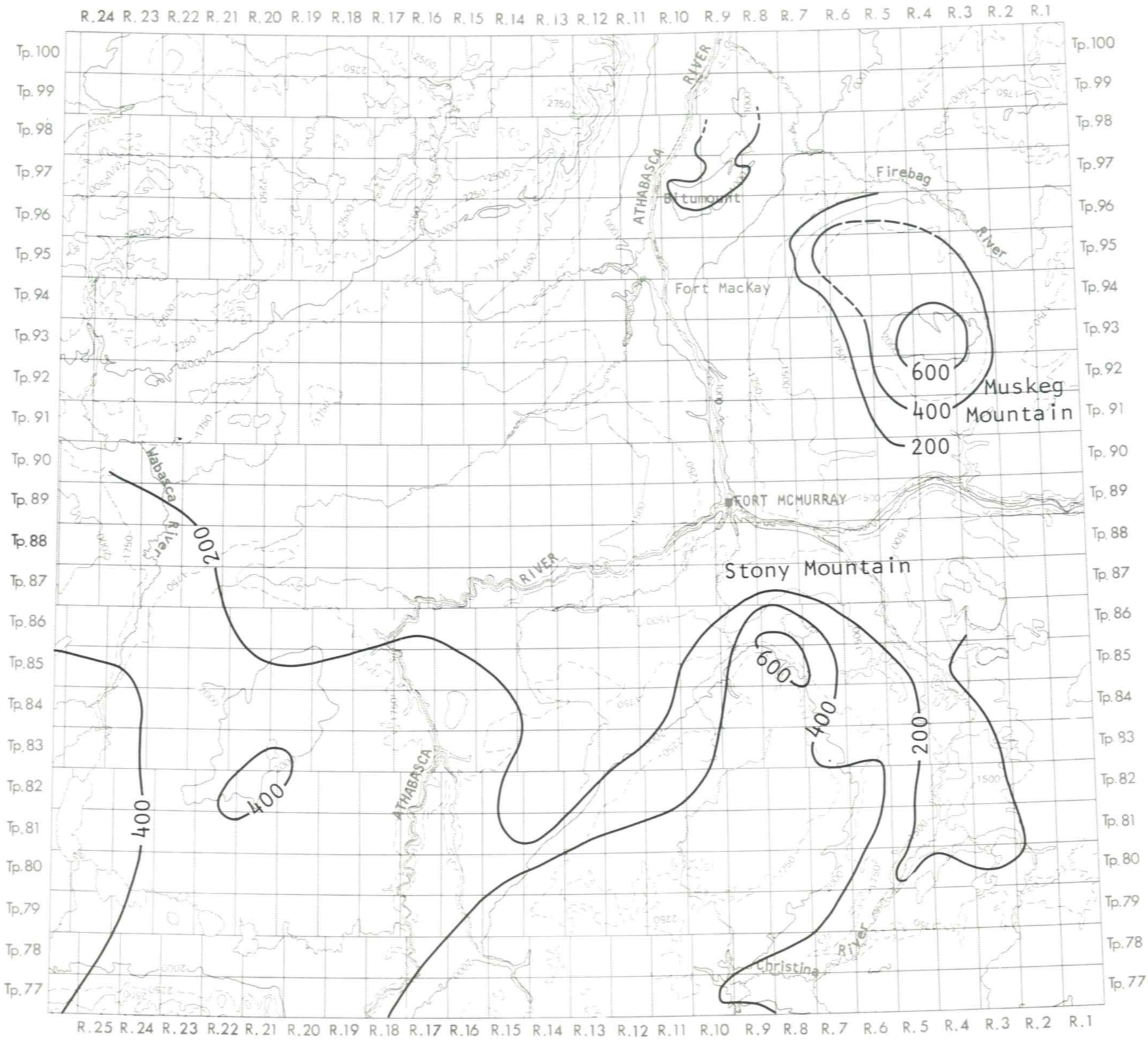
Assuming that the concentrations in the tributaries given in table 1 are valid for December 1976, and that complete mixing occurs, the chloride concentration in the Athabasca River between Fort McMurray and Embarras should increase from 19 mg/L to 19.6 mg/L. The actual value is assumed to be over 30 mg/L (Table 1). Thus the discharging groundwater that apparently contributes 4.7 m^3/sec average increase to the flow has a chloride concentration of about 472 mg/L. Chloride concentrations in the groundwater in the Devonian rocks in this area vary between 10,000 mg/L and 100,000 mg/L, so the 472 mg/L value is comparatively low. Also, the volumes and concentrations of chloride ion entering the Athabasca River from the Suncor, Inc. and Syncrude operations are unknown, so the concentration in the discharging groundwater could be even lower.

During the winter the quality of water in all secondary streams in the area is quite good (Table 1). The low values for total dissolved solids and chloride in many of the streams indicate that groundwater entering the stream travels only a very short distance in the subsurface. Detailed examination of chemical analyses of surface and subsurface water from the Muskeg River basin indicates the streamflow during the winter months is dominantly derived from the muskeg rather than from the underlying inorganic sediments (F. W. Schwartz, University of Alberta, pers. comm.). Major secondary rivers such as the Firebag, Tar, Ells, Steepbank, and Horse which have low chloride ion concentration during baseflow also probably receive a relatively large proportion of their water from muskeg or, in the case of the Ells River, from lake storage.

Other tributaries — Calumet Creek, Mackay River, Prairie Creek, Hangingstone River, and an unnamed stream in Sec 26-87-9 have comparatively high chloride ion concentrations. The Hangingstone and MacKay Rivers also show increases in chloride ion concentrations in the downstream direction (Table 1). The baseflow in these streams may therefore originate, in part, from groundwater flow systems which are larger and deeper than those apparently supporting baseflow in the Muskeg, Firebag, Tar, Ells, Steepbank, and Horse Rivers.

The Ells River originates in Gardiner Lake and two gauging stations are located along it (Loeppky and Spitzer, 1977). During December 1975, January, February, and December 1976, and January 1977, the Ells River showed a net loss in flow of 2, 9, 15, 5, and 23 percent respectively between the upper and lower gauging stations. This loss, occurring when the river was in a declining stage and under baseflow conditions, is consistent with the strong downward gradients of hydraulic head which exist in the subsurface (see section on Hydrogeology).

This does not mean that the entire section of the Ells River between the two gauging stations is contributing water to the subsurface. Rather, this reach probably consists of



many segments, some of which receive water from and others which discharge water to the ground, resulting in a net loss of flow; as well, the direction of flow in any segment may change with time. This is in keeping with the proposed model of groundwater flow in the K-Q hydrostratigraphic unit (see section on Hydrogeology). The relationship, with flow directions indicated, is depicted schematically in figure 6. Under these conditions the concentrations of chemical constituents could noticeably increase. Thus, even though no gauging stations or baseflow surveys are available, it is likely that most rivers draining the Birch Mountains have the type of relationship to the groundwater flow system depicted in figure 6. This may explain why the Tar, MacKay, and Dunkirk Rivers, all of which drain the same sort of geological and morphological terrain as the Ells River, have virtually no flow at their gauging stations during winter in spite of their large drainage areas (311, 5232, and 1582 km^2, respectively).

The data on surface water are currently not adequate to make conclusive statements regarding the interrelationship with groundwater. Present indications are that:

1) muskegs may contribute significantly to baseflow in certain streams;
2) rivers and streams draining the Birch Mountains will have very low or even negative baseflow components;
3) quality of baseflow in all rivers and streams is quite good; and
4) the volume of groundwater entering the Athabasca River through springs and seepage between Fort McMurray and Embarras is quite small.

GEOLOGY

SURFICIAL GEOLOGY

Relatively thick glacial drift is found along the eastern edge of the area and also in the southwest (Fig. 7). Muskeg Mountain and Stony Mountain are formed of thick drift

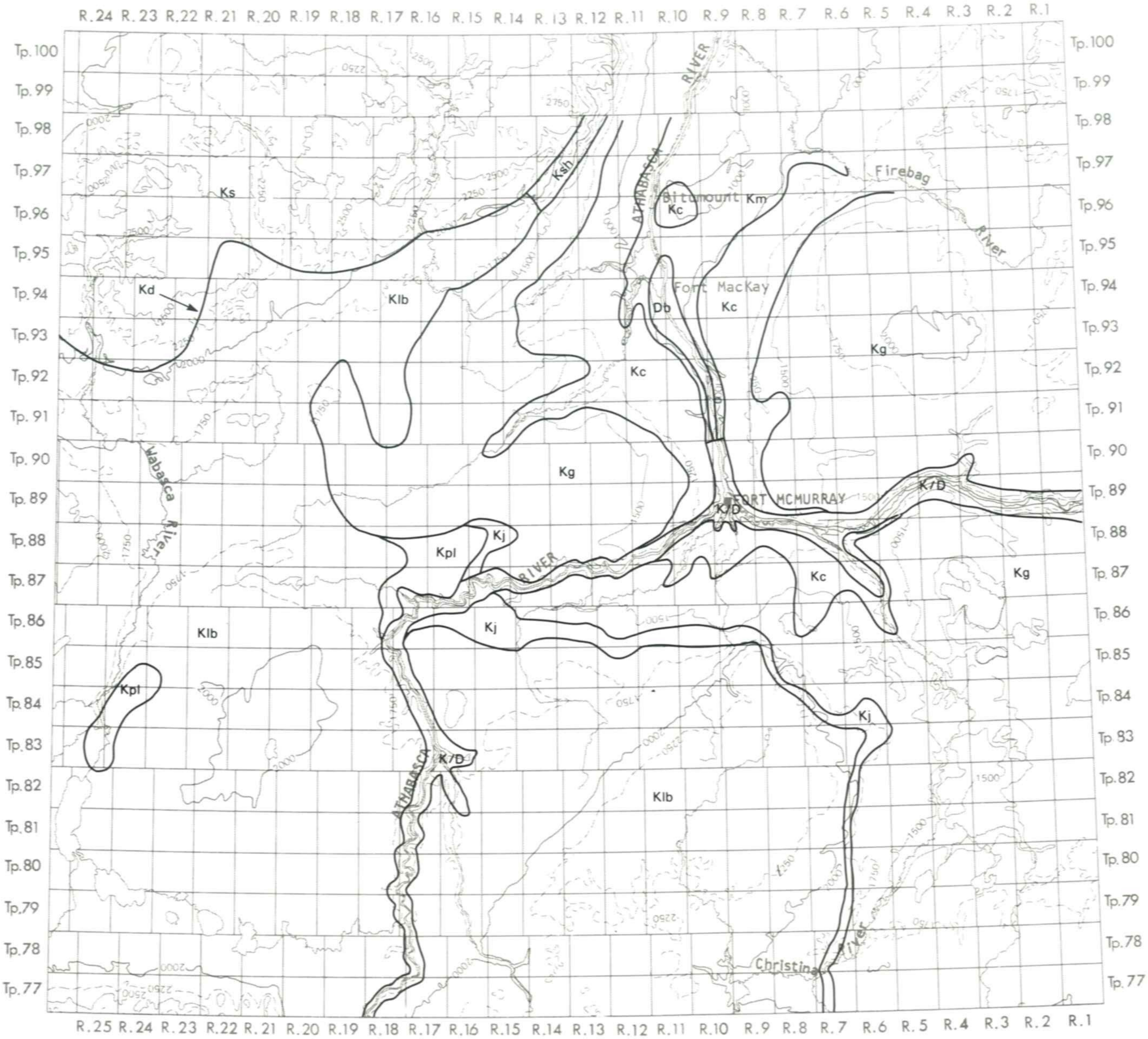


FIGURE 8. Bedrock geology

overlying minor bedrock highs. The thick drift in the southwest is associated with a buried preglacial valley system. In spite of the intensive geological exploration of the area, definitive data regarding drift thickness and character are relatively sparse. McPherson and Kathol (1975, 1977) recently examined the Fort McKay-McClelland Lake area in some detail.

BEDROCK GEOLOGY

The stratigraphic succession and dominant lithology of post-Precambrian geological units are presented in Table 2. The table has been modified from Carrigy (1973). References to original work on the stratigraphy of the area are presented on the right-hand side of this table. Major contributions to the understanding of the geology of the area have been made by Carrigy (1959, 1966, 1973). A generalized bedrock geology map is presented in figure 8.

Features of the stratigraphy that are of importance to the hydrogeology are:

1) the evaporite sequence of late Middle Devonian age;
2) the erosional unconformity separating the rocks of

Devonian and Cretaceous age; and
3) the alternating sandstone and shale sequence of Cretaceous age.

Additional description of the McMurray Formation and the distribution of oil within it is warranted, as the formation seems to constitute an unusual hydrogeological unit. The McMurray Formation is a deltaic sand deposit in a transgressive Cretaceous sequence (Carrigy, 1966). The unit tends to be coarser grained at the bottom and finer grained toward the top. Detailed lithologic correlation is difficult because of the complex facies patterns (Carrigy, 1966; Mossop, 1978).

The time of oil accumulation in the McMurray Formation is still the subject of much debate — current theories favor migration into the reservoir after deposition (Carrigy, 1966) rather than contemporaneous accumulation. The distribution of oil is controlled by the petrographic properties of the McMurray Formation. Favorable sites for oil accumulation appear to be fluviatile sands and fine-grained micaceous sands of foreset beds (Carrigy, 1966). Thus, the distribution of the viscous oil, which partially or completely fills the intergranular pores, is at least as complicated as the geometry of the deposit itself. The deposit thus cannot be viewed as a solid layer of heavy oil in a blanket sandstone unit. The degree of oil saturation varies in three dimensions in response to complex variations in the petrological properties of the host sediments (Mossop, 1978). This complex pattern of oil saturation means that the oil sands can be considered as having a finite hydraulic conductivity when viewed on a regional scale.

Lithological and geophysical logs from 15 boreholes drilled for this project have been published (Hackbarth, 1976, 1977). The locations of these holes are shown in figure 3, and geological strip logs are presented in Appendix 2.

STRUCTURE

The existence of two faults affecting the Precambrian surface (Fig. 9) is hypothesized. One, crossing the area on a north-northwest trend from Tp 81, R 3 to Tp 97, R 11, is called in this report the Sewetakun (Cree — meaning salt) Fault. The effect of the Sewetakun Fault on the hydrogeology can be determined. The other fault crosses the area on a west-northwest trend from Tp 77, R 2 to Tp 88, R 25. The primary evidence for the existence of this latter fault is a noticeable offset of regional structural contour trends; however data on this fault are very sparse, so it will not be discussed further.

Evidence for the existence of the Sewetakun Fault affecting the Precambrian consists of the following:

1) relief of 273 ft (83 m) on the Precambrian surface between holes located in Fort McMurray (Tp 89, R 9);
2) trends on gravity maps (Canada Department of Mines and Technical Surveys, 1963);
3) references to faults affecting at least the Precambrian in the vicinity (Garland and Bower, 1959; Kidd, 1951; Sproule, 1938; Carrigy, 1959; Norris, 1963); these previous investigators placed faults of north-south trend as far east in Tp 89 as R 3 and as far west as R 5; the downthrown side of all of these faults is to the west; and
4) evidence of faulting in overlying units along the same trend.

The top of the Methy Formation has a regional dip to the southwest of about 25 ft/mi (4.8 m/km) (Fig. 10). The slope steepens significantly along the Sewetakun Fault (Fig. 9). The 273 ft (83 m) difference in the elevation of the Precambrian surface between holes in Fort McMurray is almost entirely preserved at the top of the Methy Formation where the difference is 248 ft (75.6 m).

Approximately in the area of Carrigy's (1959) supposed fault, Hamilton (1969) encountered a stratigraphic build-up of the Methy Formation persisting eastward to Sec 16, Tp 89, R 3. An Alberta Research Council testhole drilled 8 km (5 mi) to the southwest (Sec 9, Tp 89, R 5) was outside the reef build-up and encountered an "off-reef" sequence of evaporites nearly 130 ft (39.6 m) thick. The structure contour map of the Methy Formation (Fig. 10) shows a rapid drop between the 400 ft and 700 ft contour lines in the northeastern part of the area (Tp 89, Rs 4-5 at Tp 101, Rs 10-11). The location of this slope may correspond in part to Carrigy's fault, or to a northwestward development of Hamilton's reef build-up.

The structure contour map of the top of the Prairie Evaporite Formation (Fig. 11) shows a regional southwestward dip of about 23 ft/mi (4.4 m/km). The effects of salt solution are apparent northeast of a line running from Tp 77, R 6 to Tp 99, R 18, and removal of the Prairie Evaporite Formation by solution is essentially complete east of the trace of the Sewetakun Fault (Fig. 9). Intense deformation, as indicated by closed depressions, generally follows the trend of the fault.

The configuration of the Paleozoic surface (Fig. 12) is the result of post-Devonian — pre-Cretaceous erosion and tectonic activity (Norris, 1963), associated with continuing salt removal by solution. More details are known about this surface near Fort MacKay because numerous boreholes have been drilled in this area due to its potential for surface mining of oil sands. It is probable that further data will show that the Paleozoic surface under the rest of the area has a similar structure. On this map, because of the uneven distribution of data points, values were averaged when more than one per square mile was available.

A major valley system on the Paleozoic surface (Fig. 12) follows the trend of the Sewetakun Fault from the southeast corner of the area to about the location of Fort McMurray. Another valley system apparently drained the southwest area and a third major system drained north through the Bitumount area. A major depression, noted previously by Carrigy (1959), is located just south of Bitumount (Tp 97, R 11). The top of the Paleozoic surface has been encountered as deep as 400 ft (122 m) above sea level at site 1 (Appendix 2) in this basin.

Deposition of the McMurray Formation was strongly controlled by the configuration of the pre-Cretaceous erosion surface (Carrigy, 1973). Sands near the base of the McMurray Formation tend to be coarse grained and, where barren of oil, are excellent aquifers. The distribution and thickness of this basal McMurray aquifer is shown in figure 13. This aquifer is over 50 ft (15 m) thick near Bitumount. This greater thickness is the result of the collapse of portions of the area, which is also indicated by permanent collapse features. Thinner, but nonetheless significant,

TABLE 2
Stratigraphic succession

	System or Series	Stratigraphic Unit	Dominant Lithology	Reference
K-Q Hydrostratigraphic Unit	Pleistocene and Recent		Till, sand, silt, and gravel	Bell (1884), Ells (1926), McConnell (1893), Green et al. (1970), Bayrock (1971), Bayrock and Reimchen (1974), McPherson and Kathol (1977)
			Erosional unconformity	
		Smoky Group	Shale	McLearn (1917)
	Upper Cretaceous	La Biche Formation	Shale	McConnell (1893)
		Dunvegan Formation	Sandstone	Wickenden (1949)
		Shaftesbury Formation	Shale	
	Lower Cretaceous	Pelican Formation	Sandstone	
		Joli Fou Formation	Shale	
		Grand Rapids Formation	Lithic sand and sandstone	
		Clearwater Formation	Shale and siltstone	
		Wabiskaw Member	Glauconitic sandstone	
		McMurray Formation	Quartzose sand impregnated with heavy oil	
			Erosional unconformity	
D-2 Hydrostratigraphic Unit	Upper Devonian	Woodbend Group		
		Grosmont Formation	Limestone reef	Crickmay (1957)
		Ireton Formation	Shale and shaly limestone	Norris (1973)
		Cooking Lake Formation	Limestone	Belyea (1952)
		Beaverhill Lake Formation	Argillaceous limestone, calcareous shale and clastic limestone	Crickmay (1966)
			Paraconformity	
		Slave Point Formation	Limestone and dolomite	
			Paraconformity	
Impermeable Layer	Middle Devonian	Fort Vermilion Formation	Anhydrite and dolomite	Allan (1920)
		Elk Point Group		Crickmay (1957)
		Watt Mountain Formation	Shale and anhydrite	McGehee (1949)
		Muskeg Formation	Anhydrite and dolomite	Norris (1963, 1973)
		Prairie Evaporite Formation	Salt and anhydrite	Greiner (1956)
D-1 Hydrostratigraphic Unit		Methy Formation	Reefal dolomite	Baillie (1953a, 1953b)
		McLean River Formation	Dolomite, claystone and evaporite	Hamilton (1969)
		La Loche Formation	Claystone and arkosic sandstone	Norris and Uyeno (1972)
				Belyea (1952)
			Erosional unconformity	
	Precambrian		Metasedimentary rocks and granite	Carrigy (1959)

[1] After Carrigy (1973)

portions of the basal McMurray aquifer are found along a line extending from Fort McMurray to just southeast of Gregoire Lake.

The McMurray Formation has been partially or completely eroded in the Athabasca River valley (Fig. 14) downstream of Tp 87. In the southwestern portion of the area the regional dip of the formation is to the southwest at about 11 ft/mi (2.1 m/km). A series of depressions extends from the southeast corner of the area, following the trend of the Sewetakun Fault (Fig. 9), to the vicinity of Fort McMurray, where the underlying soluble strata are currently being dissolved. Subsidence of the McMurray Formation is also observed near Bitumount.

The Clearwater Formation dips southwestward at about 8 ft/mi (1.5 m/km) (Fig. 15). The numerous closed depressions appearing on this map may be the result of sparse data or may be real and due to differential compaction. The Clearwater Formation subcrops or crops out for several miles back from the limit shown on figure 15, so some of the features indicated on the map may be erosional rather than structural. A depression located in the southeast corner of the area appears to overlie the trend of the Sewetakun Fault (Fig. 9); however, data are fairly sparse.

The Grand Rapids Formation dips to the southwest at about 8 ft/mi (1.5 m/km) (Fig. 16) in those areas not affected by erosion. Over large portions of the area the Grand Rapids Formation subcrops under glacial drift and the structure shown is erosional.

The slight decrease in dip between the McMurray and Clearwater Formations indicates a minor thickening of the latter to the west. A similar westward thickening is shown by Rudkin (1964) for the Lower Cretaceous in much of Alberta.

In summary, the following structural features indicate that the Sewetakun Fault exists and has affected rock units as young as Devonian in age:

1) Relief of 273 ft has been noted on the Precambrian surface between two testholes in Fort McMurray.
2) The fault trace coincides with various structural features on the surface of Devonian age units (Figs. 10, 11, and 12), including steep slopes on the top of the Methy Formation, closed depressions on the surface of the Prairie Evaporite Formation, and a deep valley system on the Paleozoic surface.
3) The coincidence of the trend of the Sewetakun Fault with the western solution limit of the Prairie Evaporite Formation (Fig. 11) seems more than coincidental — a cause and effect relationship seems reasonable.
4) A reefal build-up of the Methy Formation extends generally southwest from the trace of the Sewetakun Fault (W. N. Hamilton, Alberta Research Council, pers. comm.). The cause of this build-up could be similar to that cited by Van Hees (1958) in the Meadow Lake area of Saskatchewan where reactivation of Precambrian faults lead to a build-up of the Meadow Lake reef. In the study area, reactivation of Precambrian faults during deposition of the Methy Formation caused thicker reefal deposits on the downthrown side. The reefal build-up mentioned previously (Hamilton, 1969) is further east (Tp 89, R 3) and may be related to faults noted by Sproule (1938) and Kidd (1951).
5) Faulting affecting Devonian rocks of northeastern Alberta has been noted by Bayrock (1976), Carrigy (1959), Garland and Bower (1959), Godfrey (1953), Govett (1961), Kidd (1951), Norris (1963) and Sproule (1938). It is thus not a novel tectonic feature for the area. Features common to these faults include a general northwesterly trend for the fault and downthrow to the west.

Zones of low hydraulic heads in the Beaverhill Lake, Methy, La Loche, and McLean River Formations (Figs. 17 and 18) parallel the trend of the Sewatakun Fault. North of Fort McMurray this might be explained by the presence of the Athabasca River valley, but southeast of the town the low heads continue despite the absence of the valley. The widespread distribution of low hydraulic heads is not consistent with observed low hydraulic conductivities in the Beaverhill Lake, Methy, La Loche, and McLean River Formations (see Hydrogeology section). The most logical explanation for the pattern of hydraulic head distribution is a fractured or disturbed zone in which secondary hydraulic conductivity is much larger than the primary hydraulic conductivity observed elsewhere. Fracturing and collapse of portions of the Beaverhill Lake Formation due to solution of the underlying Prairie Evaporite Formation could account for low heads in that unit, but cannot account for the low heads in the Middle Devonian units. The hydrogeological role of the fault is explained in detail in the following sections.

HYDROGEOLOGY

GROUNDWATER FLOW

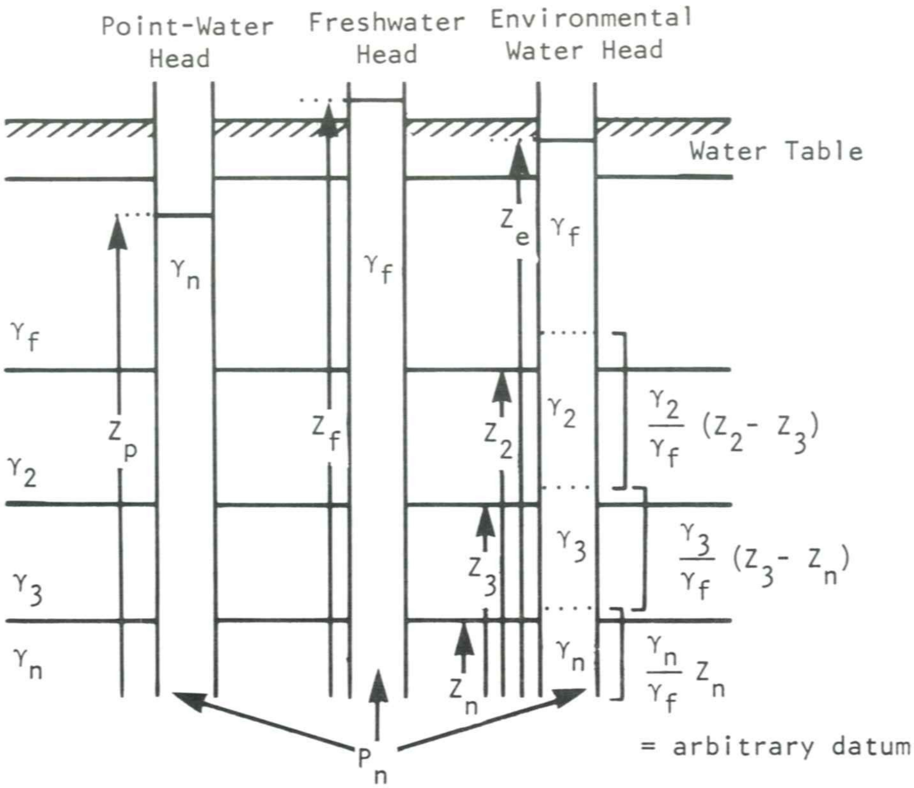
Nature of Data

Data used to interpret groundwater flow patterns include heads from water levels in observation wells and records of shut-in pressure from drill-stem tests conducted both for this project and for oil and gas exploration. Formation pressures from drill-stem tests were determined according to the method of Horner (1951) and were subsequently expressed as freshwater hydraulic heads. Maps of freshwater head for the major rock units in the area are presented in figure 17. Cross sections of the area showing contours of freshwater head are presented in figure 18.

Lusczynski (1961) demonstrated that the comparison of freshwater hydraulic heads along a horizontal plane is valid for groundwater of variable density. He also showed that the comparison of freshwater hydraulic heads along a vertical section is not strictly valid in groundwater of variable density and that an interpretation of vertical gradients should only be made using "environmmental water heads". Environmental water is defined to be the water of constant or variable density occurring along a vertical between the point of interest and the top of the zone of saturation (Lusczynski, 1961). The relationships between point-water head, freshwater head, and environmental water head are as shown in figure 19. Expressed mathematically, these relationships are:

Point-water head

$$Z_p = \frac{P_n}{\gamma_n} \qquad (1)$$



where:

γ_n - specific weights of liquids; f - freshwater

$\gamma_f \leq \gamma_2 \leq \gamma_3 \cdots \leq \gamma_n$

Z_n - elevation above an arbitrary datum;

Z_p, Z_f, Z_e - the hydraulic head

P_n - pressure at bottom of observation well

FIGURE 19. Point-water, freshwater, and environmental-water hydraulic heads

Freshwater head

$$Z_f = \frac{P_n}{\gamma_f} \qquad (2)$$

Environmental water head (after Lusczynski, 1961)

$$P_n = \gamma_f (Z_e - Z_2) + \gamma_2 (Z_2 - Z_3) \ldots \gamma_{n-1}(Z_{n-1} - Z_n) + \gamma_n Z_n$$

rearranging

$$Z_e = \frac{P_n}{\gamma_f} - \left[\frac{\gamma_2}{\gamma_f}(Z_2 - Z_3) \ldots + \frac{\gamma_{n-1}}{\gamma_f}(Z_{n-1} - Z_n) + \frac{\gamma_n}{\gamma_f} Z_n\right] + Z_2 \qquad (3)$$

where γ_n, P_n, Z_n are as defined in figure 19.

Stated in words: the environmental water head is the freshwater head

$$\frac{P_n}{\gamma_f}$$

reduced by an amount corresponding to the salt mass in the system. Depending upon the ratios of the specific weights of the liquids, the quantity "Z_2" will be nearly equal to the quantity in brackets.

If the specific weight of the liquid can be expressed as a function of depth, ($\gamma = f(Z)$) then equation (3) takes the form:

$$P_n = \int_0^{Z_e} f(Z)\, dz$$

which can be solved for the unknown Z_e. In practice the distribution of density of water chemistry is seldom sufficiently well known to be characterized by a continuous mathematical expression. This factor makes the calculation of a valid environmental water head very difficult.

The point-water head is the hydraulic head which is actually measured in an observation well or piezometer. Freshwater head (a special case of point-water head) and environmental water head are calculated quantities. The maps of total dissolved solids content (Fig. 23) demonstrate that the groundwater is indeed of widely variable composition and that below the Prairie Evaporite Formation total dissolved solids concentrations reach 300,000 mg/L. The specific gravity of a sodium chloride solution of this concentration is about 1.18 (Fig. 20).

Most groundwater above the Prairie Evaporite Formation, except as Site 1 and in the southwest corner of the area, has a total dissolved solids content of less than 50,000 mg/L. The specific gravity of a 50,000 mg/L sodium chloride solution is about 1.032 (Fig. 20). Under these circumstances the difference in freshwater head and environmental water

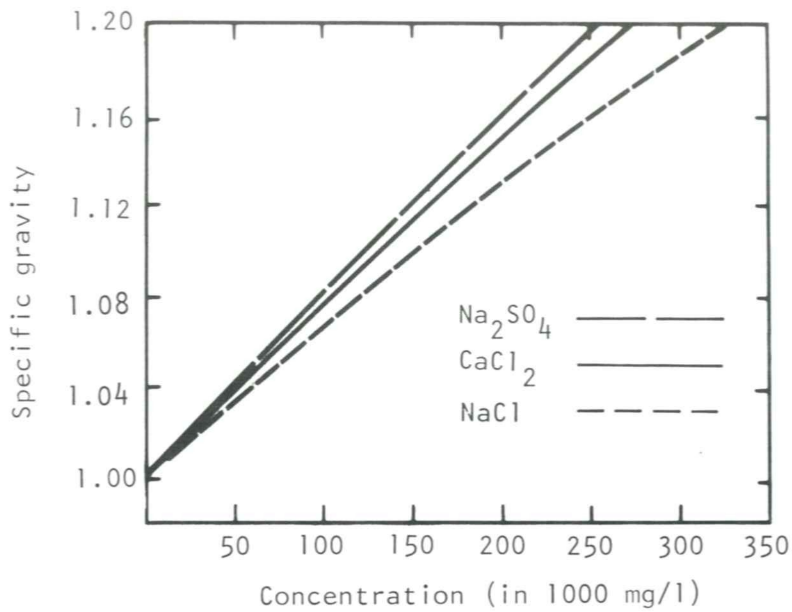


FIGURE 20. Specific gravity of aqueous solutions

head is about 3 percent and cannot be considered significant. Thus the use of freshwater hydraulic head values in both the horizontal and vertical directions is acceptable for all rock units above the Prairie Evaporite Formation.

West of the Sewetakun Fault the Prairie Evaporite Formation acts as an impermeable barrier. No vertical flow takes place across that unit from the Methy Formation to the Beaverhill Lake Formation or vice versa, and it is therefore irrelevant how the hydraulic head in the former unit is expressed. For consistency, however, the use of freshwater head is continued for units below the Prairie Evaporite Formation.

Additional Influences on Hydraulic Head

Bredehoeft and Hanshaw (1968) have cited nine mechanisms in addition to aquifer head that possibly contribute to the pressure head measured at any point in an aqueous system: 1) tectonic compression; 2) loading and compaction; 3) fossil pressures corresponding to greater amounts of effective stress; 4) magmatic intrusions; 5) infiltration of gas; 6) solution or precipitation of minerals; 7) mineral phase change (for example, gypsum to anhydrite; montmorillonite to illite); 8) fluid volume change due to temperature change; and 9) osmotic membrane phenomena.

Tectonic compression is inconsequential in this area. Also, given the ages of the rocks and the fact that this is not an actively subsiding basin, loading and compaction are considered unimportant. Magmatic intrusions are not present in this area. Infiltration of gas may affect hydraulic heads, but is not regarded as a significant factor. Fluid volume change due to temperature changes is unlikely to be significant due to the low geothermal gradient.

Fossil pressures corresponding to greater amounts of effective stress have been hypothesized by Tóth (Alberta Research Council, per. comm.) in the Middle Devonian strata of an area just to the west of the Athabasca Oil Sands area. He found evidence that the potentiometric surface of rocks of Middle Devonian age coincides with a Pliocene land surface that was likely several hundred feet higher than the present land surface. It is also possible that rock units are still expanding in response to removal of the Pleistocene ice load. This would cause a lowering of hydraulic heads in those units where water could not move in fast enough to fill the expanding pore volume. Solution or precipitation of minerals which results in a change in pore volume is probably not taking place.

Mineral phase change, particularly that of gypsum to anhydrite or the reverse, could possibly affect hydraulic heads in Devonian rocks due to the large volumes of those minerals present. Within the ranges of temperature, depth, and salinity observed in the area, gypsum is the stable phase, yet anhydrite is commonly referred to as being present (Norris, 1973; Hamilton, 1969; Carrigy, 1959). Since the conversion of anhydrite to gypsum consumes water, it is possible that this reaction is causing lower hydraulic heads adjacent to the anhydrite than might otherwise be expected.

Osmotic membrane phenomena may possibly be occurring in the area and might account for the large hydraulic head difference between the Beaverhill Lake and Methy Formations (Fig. 17 and 18). Theories on osmotic phenomena present shale or clay layers as the membrane between waters of differing salinities (Back and Hanshaw, 1965). Such shale layers do not exist in the Prairie Evaporite Formation; moreover, it seems likely that osmotic movement of water would be short-lived because the migrating water itself would rapidly become salt-saturated in moving through the evaporites.

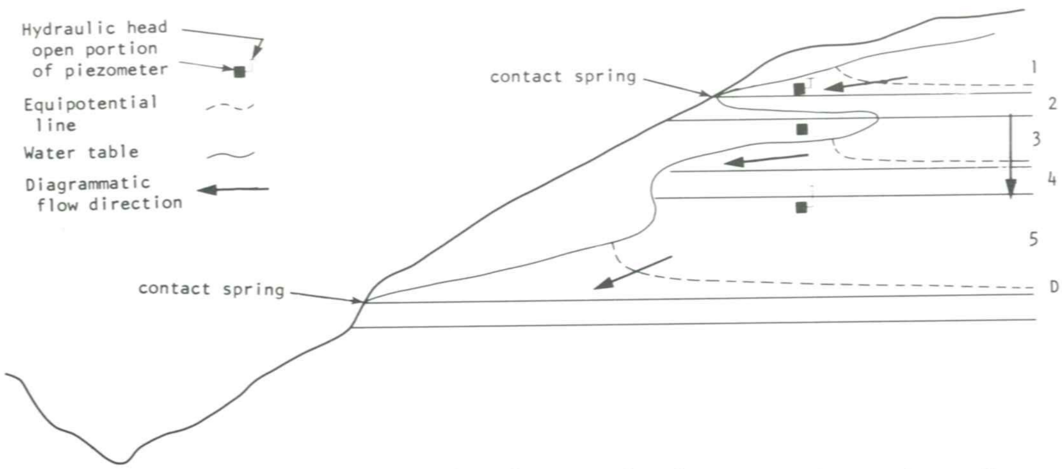


FIGURE 21. Diagrammatic cross section of saturated and unsaturated groundwater flow regime

Hydrogeological Setting West of the Sewetakun Fault

The hydrogeological setting west of the Sewetakun Fault can be simplified by defining it in terms of hydrostratigraphic units (Maxey, 1964). West of the Sewetakun Fault three hydrostratigraphic units can be defined. The upper unit, consisting of the glacial drift and the Cretaceous formations, is called the *K-Q hydrostratigraphic unit.* The middle unit consists of the Woodbend Group and Beaverhill Lake Formation and is called the *D-2 hydrostratigraphic unit.* The lower unit, consisting of the Methy, McLean River, and La Loche Formations, is called the *D-1 hydrostratigraphic unit* (Table 2). As mentioned previously, the evaporite sequence lying between the D-2 and D-1 hydrostratigraphic units acts as an impermeable barrier.

K-Q hydrostratigraphic unit — This unit is characterized by values up to 2.3 for "vertical hydraulic gradient" (Appendix 2). In a homogeneous water-saturated medium this value can only approach unity (one unit of head loss or gain per one unit of vertical distance). However, the K-Q hydrostratigraphic unit is not homogeneous, but consists of alternating layers of highly contrasting hydraulic conductivity. This non-homogeneity, combined with relatively large local relief, creates high vertical gradients, but is not sufficient to explain gradients in excess of unity.

Another naturally occurring situation which would account for high vertical hydraulic gradients is the development of unsaturated zones in the ground as shown in figure 21. Calculation of a vertical hydraulic gradient between the upper and lower piezometers would give a high value but would not be meaningful because the potential field is interrupted by a zone where unsaturated flow is taking place. Use of the term "unsaturated flow" in this report follows that of Freeze (1967) who stated that unsaturated flow takes place where the pressure head is negative and that saturated flow takes place where the pressure head is positive. The water table separates zones of saturated flow from unsaturated flow.

At sites numbered 3, 12, and 16 (Appendix 2) piezometers were completed in dry zones similar to the one indicated in figure 21. An unsaturated zone is indicated at site 13 (Appendix 2) at a depth of about 500 to 700 ft (152 to 213 m) even though the well is not dry, because the head in the 750-ft (229-m) well is not above the top of the aquifer in which it is located. Since the distances to outcrop of the unsaturated unit are 6 mi (10 km) at site 3, 10 mi (16 km) at site 13, and about 1 mi (2 km) at both sites 12 and 16, it is apparent that unsaturated zones can extend a significant distance from outcrop. These unsaturated zones are shown on the cross sections (Fig. 18) and schematically in figure 21.

Layering of unsaturated and saturated zones has been observed in regional groundwater studies in Nevada (Mifflin, 1968), in geotechnical studies in Alberta (Eigenbrod, 1972), and in groundwater studies in small basins in the foothills of Alberta (Stevenson, in preparation). However, the location and nature of these zones is not well documented. As shown in figure 21, the water table is continued through units of both low and high hydraulic conductivity.

In figure 21 layers 1, 3, and 5 represent rock units which act as drains, conducting flow dominantly in a horizontal direction. Corresponding units in the K-Q hydrostratigraphic unit might be the basal McMurray aquifer, the Wabiskaw Member, the Grand Rapids Formation, and portions of the glacial drift. Within these units it is likely that unsaturated portions extend a considerable distance away from the outcrop.

Contact springs (Fig. 21) should be an observable indicator of the flow pattern within the K-Q hydrostratigraphic unit, and a few such springs have been observed. However, the widespread presence of muskeg and the generally high hydraulic conductivity of the glacial drift tend to mask these features.

The frequency distribution of hydraulic conductivities obtained from drill-stem and pumping tests is presented in figure 22. Also included in this diagram are laboratory data from Clark (1960) for repacked oil sand samples. The complete distribution of hydraulic conductivity values for glacial drift and the Grand Rapids Formation is not shown

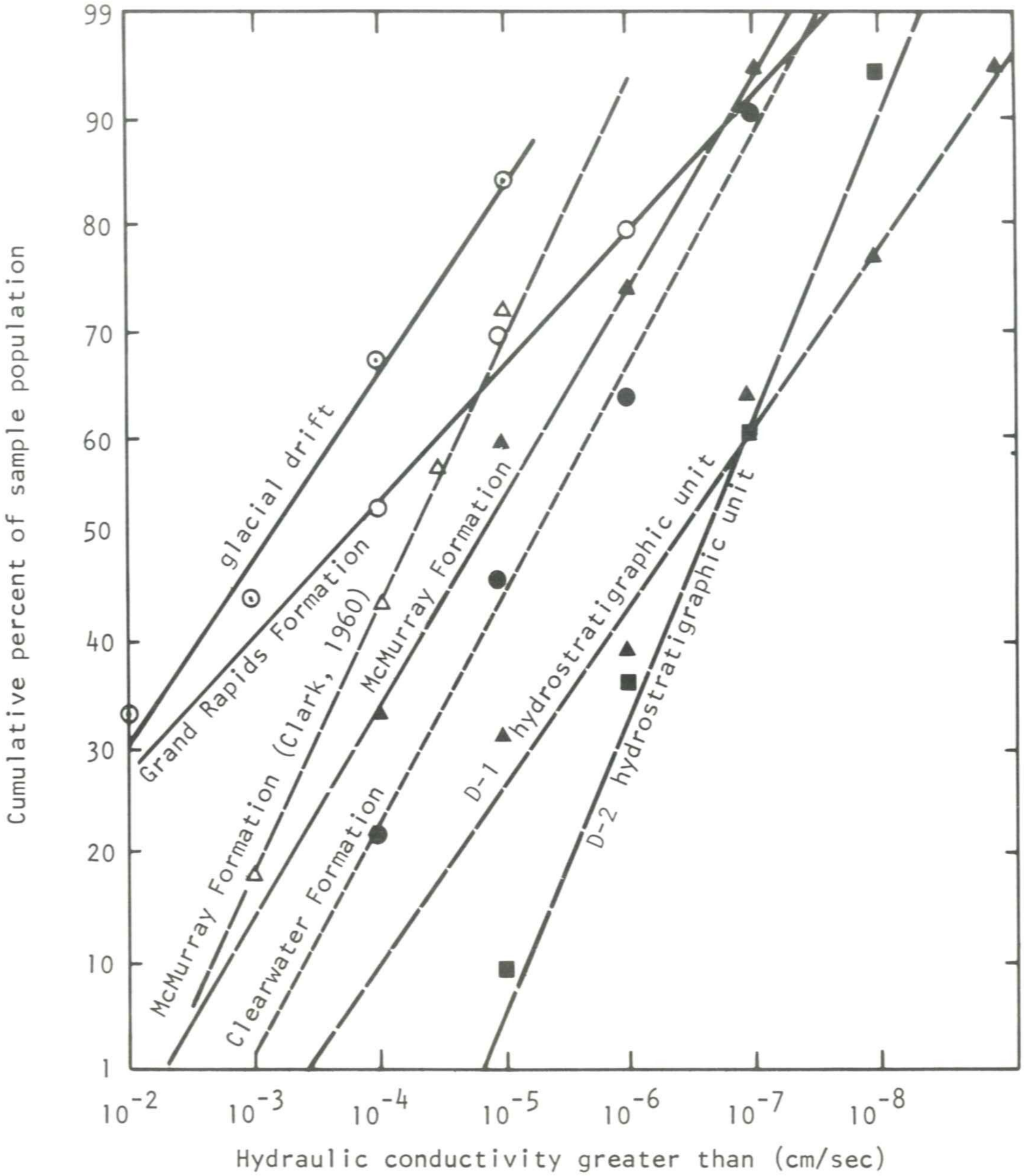


FIGURE 22. Frequency distribution of hydraulic conductivity for selected formations

but it is evident that the bulk of observed values will be quite high — probably in excess of 10^{-4} cm/sec. The hydraulic conductivities of the Clearwater and McMurray Formations show good log-normal distributions. The median hydraulic conductivity value for the McMurray Formation (3.2×10^{-5} cm/sec) probably represents those portions with low oil contents. The combination of these relatively permeable units with the large local relief promotes widespread extension of unsaturated zones inward from the outcrop (Fig. 18).

D-2 hydrostratigraphic unit — This unit is characterized by hydraulic heads lower than those in the overlying McMurray Formation (Figs. 17b,c and 18). Groundwater flows downward into this unit and then laterally toward the northeast.

The distribution of hydraulic conductivity data in the D-2 hydrostratigraphic unit, as measured by drill-stem and pumping tests, is shown in figure 22. The median of the distribution is about 3.2×10^{-7} cm/sec.

The distribution of hydraulic head in the Upper Devonian hydrostratigraphic unit is consistent with that presented at a much smaller scale by Hitchon (1969a, 1969b), who demonstrated that the Upper Devonian and Carboniferous carbonate rocks of the Alberta basin have relatively low hydraulic heads and that flow is into these units and subsequently towards the northeast corner of the province. Specifically, Hitchon (1969a) states "The drain essentially channels flow from the entire Alberta basin and discharges it in the region of the Athabasca oil sands." He attributed the low fluid potentials of the drain to highly permeable reef complexes in the Woodbend Group and Beaverhill

Lake Formation. The permeability of the Beaverhill Lake Formation in established fields is 1.2×10^{-5} to 1×10^{-4} cm/sec (Moyer, *et al.,* 1964). However, the Beaverhill Lake Formation is not reef-bearing in the study area. The low hydraulic conductivity and the fact that the unit generally lies below the level of the Athabasca River are not consistent with the low hydraulic heads observed in this unit.

The widespread distribution of low heads in the D-2 hydrostratigraphic unit is probably related to fracture permeability developed along the Sewetakun Fault and to collapse of areas of that unit due to solution of underlying salt. The fault acts as a vertical drain, lowering the hydraulic heads adjacent to it (Figs. 17c and 18) to approximately the level of the Athabasca River. Groundwater from both the D-2 and D-1 hydrostratigraphic unit flows upward along the fault zone (Fig. 18). This upward flow has enhanced solution of the Prairie Evaporite Formation and subsequent collapse of the Beaverhill Lake Formation at, for instance, Bitumount (Fig. 12). Conversion of anhydrite to gypsum may be contributing to the low hydraulic heads in the vicinity of the Sewetakun Fault where active solution of the evaporite is taking place. Reduction of hydraulic head would occur if groundwater was unable to move toward the reaction zone as rapidly as it was being incorporated into the anhydrite crystal lattice to form gypsum. The conversion of anhydrite to gypsum releases about 4000 calories of heat per mole; a detailed examination of geothermal gradients in the area might reveal if the reaction is, in fact, important enough to affect hydraulic heads. Available data (see section on Groundwater Temperatures) do not indicate excessive temperature values.

Evaporites — This sequence, of Middle Devonian age, acts as an impermeable barrier separating the D-2 and D-1 hydrostratigraphic units. The evidence for this is:

1) West of the zone where thinning of the evaporite sequence takes place (Figs. 11 and 18), there is little recognizable evidence of solution of the Prairie Evaporite Formation either structurally (Fig. 11) or stratigraphically (W. N. Hamilton, Alberta Research Council, pers. comm.). If water were moving upward through the evaporites, one would expect solution of the salt to be evident.
2) The evaporite deposits contain significant amounts of anhydrite, but gypsum is the stable mineral phase (Hanshaw and Bredehoeft, 1968) for the temperatures, depth, and salinities of water observed adjacent to the evaporite sequence. Water moving across the evaporites would be consumed in a conversion of anhydrite to gypsum and would no longer be part of the groundwater flow system.
3) The hydrochemistries of the D-2 and D-1 hydrostratigraphic units are strongly contrasting (Figs. 23d, 23e and 24). If upward flow were taking place through the evaporites, one would expect much more saline water in the D-2 hydrostratigraphic unit.

D-1 hydrostratigraphic unit — This unit was defined west of the Sewetakun Fault and is characterized by a piezometric surface which corresponds to the land surface (Figs. 17d and 18) and by very high concentrations of dissolved material (Figs. 23e and 24). Groundwater flow in this unit is northeastward up the regional stratigraphic dip (Fig. 18b and 18e). Freshwater hydraulic heads decline rapidly to less than 800 ft (244 m) near the Sewetakun Fault indicating that the fault acts as a connection between this unit and the surface. On the map, the fresh-water head contours (Fig. 17d) tend to parallel the trend of the fault.

It is in fact interesting that zones of low hydraulic head parallel the trend of the Sewetakun Fault in the Beaverhill Lake, Methy, McLean River, and La Loche Formations (Fig. 17c and 17d) (that is, in both the D-1 and D-2 hydrostratigraphic units). Most likely the pattern of hydraulic head distribution follows a fractured or disturbed zone related to the fault in which secondary hydraulic conductivity is much larger than the primary hydraulic conductivity observed elsewhere.

Hydrogeological Setting East of the Sewetakun Fault

The separation of the Devonian rocks into two distinct hydrostratigraphic units is not valid east of the Sewetakun Fault. Most of the evaporite sequence is not present, and it appears that all of the Devonian rocks behave as one hydraulic system. Hydraulic heads in the Methy, MacLean River, and La Loche Formations are about equal to those in the overlying Beaverhill Lake Formation (Figs. 17c, 17d, and 18). The differences in water chemistry between the D-1 and D-2 hydrostratigraphic units noted farther west are not present east of the fault where waters in the Beaverhill Lake Formation and in the D-1 hydrostratigraphic unit are chemically similar (Figs. 23d, 23e, and 24).

The characteristics of the K-Q hydrostratigraphic unit are also somewhat different east of the fault. The strong downward vertical gradients within the unit, the pattern of horizontal flow in permeable units, and the vertical flow in less permeable units are observed in upland areas (Fig. 18) but not in the lowland region adjacent to the Athabasca River. In this region the hydraulic heads in all hydrostratigraphic units are very nearly equal.

The Role of the Athabasca River

Cross section E-E' (Fig. 18e) follows approximately the course of the Athabasca River through the area (Fig. 17). The upper boundary of the section is defined as the hydraulic grade line of the Athabasca River closest to the line of section. This section shows that the Athabasca River valley upstream from Fort McMurray does not appear to act as a discharge area for regional groundwater flow. In this reach of the river, groundwater moves upward toward the river only from depths less than about 400 ft (122 m) — downward flow beneath the river occurs in portions of the K-Q and D-2 hydrostratigraphic units.

The distribution of hydraulic heads downstream from Fort McMurray as shown in figure 18e is consistent with that predicted by current groundwater theory — the Athabasca River acts as the locus of the major low in the hydraulic head distribution for all geological units. This does not mean, however, that the river is an area of major volumes of groundwater discharge. Most water infiltrating into the K-Q hydrostratigraphic unit leaves through one of the horizontal drains of high hydraulic conductivity and enters the Athabasca River as tributary streamflow. The hydraulic conductivities of the D-2 and D-1 hydrostratigraphic units are so low that only small amounts of groundwater flow from these units into the Athabasca River regardless of the potential gradient. This was alluded to in an earlier discussion where it was shown that virtually no groundwater flows into the Athabasca River in this reach.

The application of the predictive mathematical models conventionally used in groundwater hydrology which consider major rivers and major hills as boundaries thus may be incorrect for some reaches of the Athabasca River. Downstream from Fort McMurray the model may be valid; however, upstream from Fort McMurray the application is invalid, as a considerable amount of flow takes place parallel to the direction of river flow.

The characteristics of groundwater flow in the area of study are, in summary:

1) Alternating layers of relatively low and high hydraulic conductivity combined with great local relief result in dominantly vertical or dominantly horizontal flow directions respectively (Fig. 18a, 18b and 18d). These conditions result in a complex series of "perched" groundwater flow systems in which unsaturated conditions may extend many miles into a rock unit from its subcrop or outcrop. These conditions are characteristic of the K-Q hydrostratigraphic unit.
2) Some of the lowest hydraulic heads observed in the area are found in the D-2 hydrostratigraphic unit (Fig. 17 and 18). Groundwater flow is dominantly horizontal and is strongly influenced by the pre-Cretaceous erosion surface and collapse features near the Sewetakun Fault.
3) The D-1 hydrostratigraphic unit is characterized by freshwater hydraulic heads (Fig. 17d) commonly far greater than those in overlying units and which rise approximately to land surface. Flow is dominantly updip (Fig. 18) except in the northeast quarter of the map area where the flow is mainly downdip.
4) The Prairie Evaporite Formation acts as a very poorly permeable confining bed for the D-1 hydrostratigraphic unit in those portions of the area west of the Sewetakun Fault (Fig. 18a and 18b).

HYDRAULIC CONDUCTIVITY OF OIL SANDS

The hydraulic conductivity of oil sands is considered for the purposes of this study to be the permeability to water of the combination of McMurray Formation and heavy oil. The amount of heavy oil present exerts a strong control on the hydraulic conductivity of oil sands (Clark, 1960) and, as stated previously, the degree of heavy oil saturation varies widely in three dimensions. Therefore, the hydraulic conductivity of the oil sands, considered on a scale of tens to hundreds of metres, is finite, and significant quantities of water will pass through them. The heavy oil acts to reduce, but definitely not to eliminate, hydraulic conductivity (Hackbarth, 1978b). Water is visualized as moving through intergranular pores not filled completely with bitumen — it is not hypothesized that the water film or envelope of each sand grain (Cottrell, 1963) participates in the movement. One could think of the combination of sand grains, water envelope, and bitumen as a solid having a very small — but nonetheless finite — hydraulic conductivity which is much lower than that of the sand grains alone. It should be emphasized that the above statements are made in the context of a regional hydrogeological study. Regional groundwater flow patterns develop over periods of time measured in millions of years. The rate at which patterns change, and the patterns themselves, are controlled, by and large, by the distribution and rate of change of the regional topography and geology as well as by variations in climate. Because of this, time is an important parameter. Flow rates which might be considered effectively nil for purposes of short-term well hydraulics are significant over the longer times involved in regional groundwater flow.

Clark (1960) stated that the permeability of oil sand becomes zero at bitumen saturations exceeding 90 percent and that permeability seems to vary inversely with saturation below this limiting value. In fact the equipment used to measure these permeabilities apparently had a lower limit of accuracy of about 10^{-6} cm/sec which was stated, somewhat erroneously, to be zero when it should have been considered to be zero only for purposes of that study. Secondly, laboratory measurements of permeability are small-scale tests which do not account for field properties of the material, such as jointing and variations in bitumen saturation, which act to increase the regional hydraulic conductivity. Nor do the tests account for such disturbances as repacking of oil sand in the column or expansion of "undisturbed" samples (Dusseault, 1977a).

If the frequency of occurrence of the permeability values (converted to hydraulic conductivity) which Clark (1960) actually obtained are plotted (Fig. 22), the distribution coincides, approximately, with that obtained from drill-stem and pump tests. The slightly higher values are to be expected due to expansion or repacking of the sample. The distribution of hydraulic conductivities for the McMurray Formation presented in figure 22 is representative of all grades of bitumen saturation since it matches Clark's distribution which is definitely for all grades of saturation. It then follows that hydraulic conductivities of the oil sands will be predominantly between 1×10^{-3} and 3.2×10^{-6} cm/sec. Hydraulic conductivities are anticipated to be less than about 3.2×10^{-6} cm/sec for 10 percent of the oil sands deposit.

Other evidence also indirectly indicates that significant regional groundwater flow does take place through the oil sands:

1) Construction of the flow nets (Fig. 18) did not require any special consideration for the McMurray Formation; that is, the data utilized to construct these diagrams did not require that the McMurray Formation be treated differently from other units of low hydraulic conductivity.
2) Well number 7-135 (Appendix 2) is completed in a 50 ft (15 m) thick low-bitumen sandstone and shale zone underlying 60 ft (18 m) and overlying 40 ft (12 m) of good quality oil sand. Pumping tests revealed an average hydraulic conductivity of about 3.8×10^{-5} cm/sec. The total dissolved solids content of water from this well has been quite stable at about 960 mg/L. The

annual water level hydrograph for this well is comparable in character to hydrographs from other wells of similar depth that are completed elsewhere in units other than the McMurray Formation. There is no evidence in the data gathered from this well to indicate special conditions within the oil sands themselves.

3) Figure 23d shows that the total dissolved solids content of groundwater from the D-2 hydrostratigraphic unit is not likely to exceed 10,000 mg/L over most of the study area. If the permeability of the McMurray Formation were extremely low or zero it would be necessary for all water in these units to have been derived from outside the limits of the oil sands and to have migrated laterally. If this were true, given the average of hydraulic conductivity of the D-2 hydrostratigraphic unit (3.2 x 10^{-7} cm/sec (Fig. 22), the concentrations of dissolved constituents would be expected to be higher.

GROUNDWATER CHEMISTRY

Total dissolved solids and chloride ion concentrations are presented in figures 23 and 24. Data used to construct these maps and cross sections consisted of chemical analyses from observation wells and drill-stem tests.

Groundwater in the K-Q hydrostratigraphic unit usually has a total dissolved solids concentration less than 5000 mg/L and chloride ion concentration less than 2000 mg/L. Occasionally the McMurray Formation may contain water having up to 10,000 mg/L total dissolved solids and 5000 mg/L chloride ion. Much higher values are observed in this unit close to the Sewetakun Fault near Site 1 (Appendix 2), where concentrations exceed 200,000 mg/L and 100,000 mg/L for total dissolved solids and chloride ion, respectively.

Low concentrations of dissolved material at depth testify to the strong downward component of groundwater flow in the K-Q hydrostratigraphic unit (Fig. 24). At Site 10 (Appendix 2) a total dissolved solids concentration of less than 5000 mg/L at a depth of about 1800 ft (550 m) is low compared to water at even shallower depths in similar rock units in Alberta (Tokarsky, 1971; Currie and Zacharko, 1976). Vertical groundwater flow rates must be quite rapid for water to reach this depth with such a low dissolved solids concentration after passing through rock consisting of shale and bentonites. This implies that topographic features such as the Birch Mountains, Stony Mountain, and Thickwood Hills exert a major influence on the groundwater flow in the K-Q hydrostratigraphic unit, and this influence is reflected in the strong vertical gradients observed at many locations in the K-Q unit (Figs. 18a, 18c and 18d).

A significant difference in chemistry exists between the D-2 and D-1 hydrostratigraphic units. The few data available (see sites 11, 12, 14, Appendix 2) indicate that rapid increases in total dissolved solids contents take place within the Prairie Evaporite Formation rather than at the base of the D-2 hydrostratigraphic unit. This suggests that significant upward flow of groundwater from the Prairie Evaporite Formation into the D-2 hydrostratigraphic unit does not take place; otherwise greater concentrations of dissolved material would be observed in the lower portion of the D-2 unit.

Hitchon (1964) has noted that a strong correlation exists between chloride ion and total dissolved solids concentrations in formation waters of western Canada. This phenomenon is indicated by the close similarity of the distribution patterns of chloride ion and total dissolved solids (Figs. 23 and 24) in the deeply buried formations. This parallelism of contours indicates that chemical conditions do not change abruptly — that conditions are reasonably uniform.

The influence of the strong downward hydraulic head gradients on the distribution of chemical constituent is indicated in figures 23 and 24. For rock units not deeply buried, the mapped contours of chloride ion concentration commonly cross the total dissolved solids contours at high angles, indicating rapid lateral changes in the anion component of the hydrochemistry. This lateral change in chloride ion concentration is caused by the downward movement of groundwater having lesser concentrations of that anion. Groundwater movement is more rapid at shallower depths than at greater depths and therefore variations in chemistry may be abrupt; in contrast, chemical conditions in deeply buried rock units are more uniform due to slowly changing hydrogeological conditions.

GROUNDWATER TEMPERATURES

Groundwater temperature data (Fig. 25 and Appendix 2) were taken using a maximum-reading thermometer

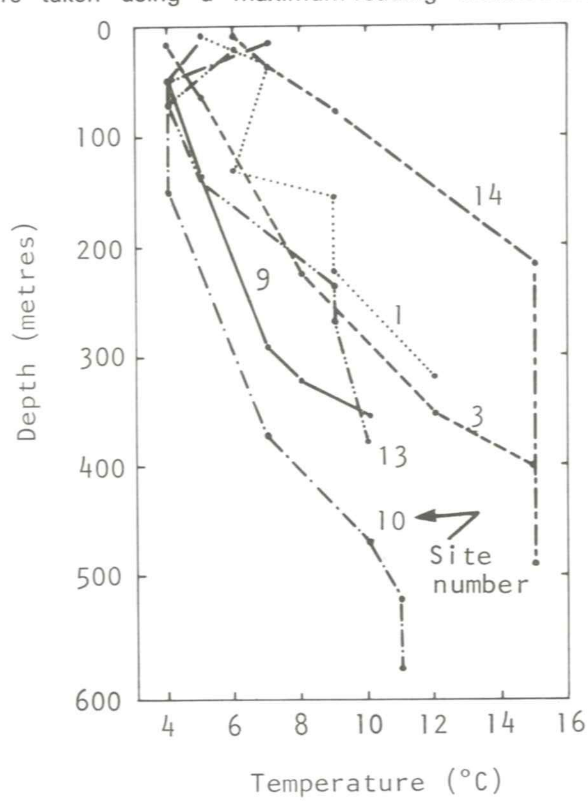


FIGURE 25. Bottom-hole temperatures in selected observation wells — July, 1977

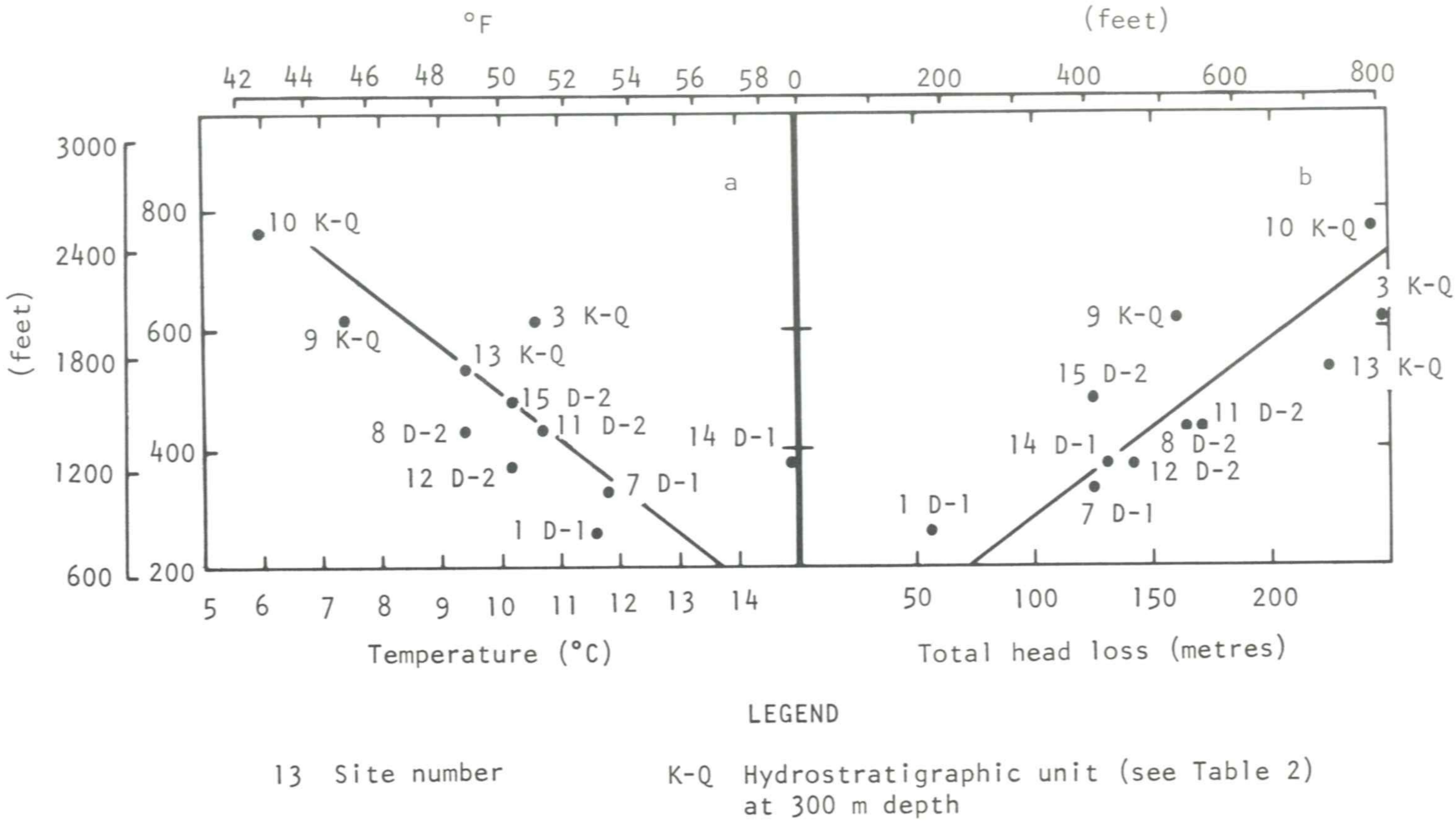


FIGURE 26. Elevation of land surface versus: (a) interpolated temperature at 300 m (1000 ft) depth; (b) hydraulic head-loss to 300 m (1000 ft) depth

suspended inside a water-sample bailer. Details of the measuring technique are given in Hackbarth (1978a).

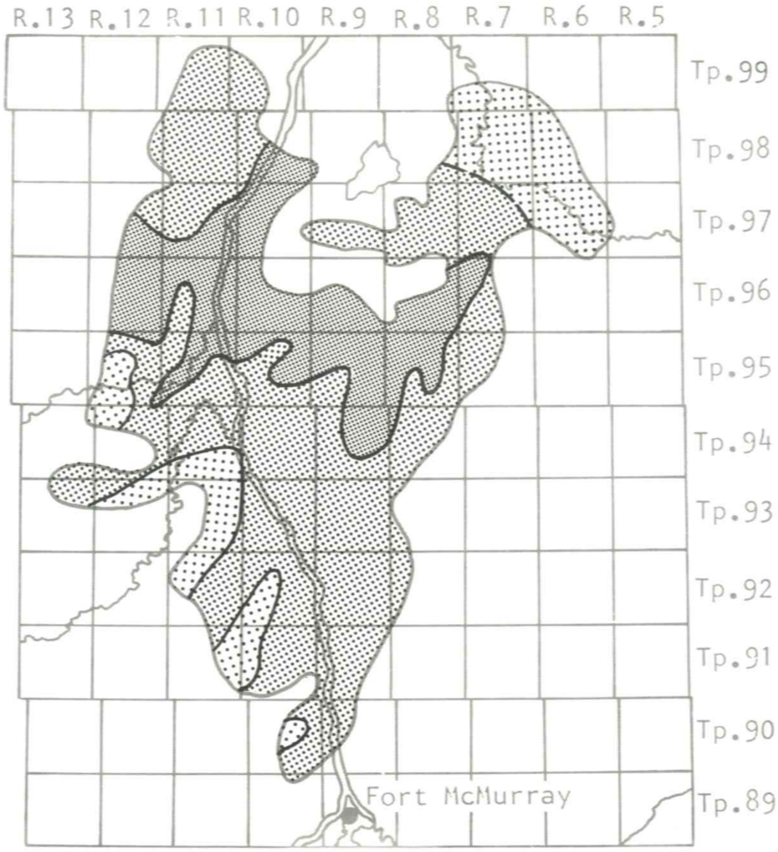
Temperatures vary considerably from site to site (Fig. 25). There is a 9°C difference in temperature at a depth of 200 m (656 ft) between sites 10 and 14 located 72 km (45 mi) apart. Sites 13 and 14, located 20 km (12 mi) apart, exhibit a 7°C temperature difference at 200 m.

The relationship of interpolated temperature at a depth of 300 m (1000 ft) to the elevation of the land surface is shown in figure 26a. There is a good linear correlation between the interpolated temperature and elevation. It is also evident from figure 26a that temperatures at a depth of 300 m (1000 ft) tend to be related to the hydrostratigraphic unit existing at that depth. Temperatures at a depth of 300 m (1000 ft) generally increase from K-Q to D-2 to D-1 hydrostratigraphic units.

The relationship between land-surface elevation and hydraulic head loss to a depth of 300 m (1000 ft) (assuming a water table at the land surface) is shown in figure 26b. A good linear relationship is also evident in this plot, as is a strong relationship of hydrostratigraphic unit to head loss. At a depth of 300 m (1000 ft) the hydraulic head loss from the surface steadily declines from the K-Q to the D-2 to the D-1 hydrostratigraphic units. Others things being constant, the greater head loss in the K-Q hydrostratigraphic unit implies that the volumes of water moving downward are larger in that unit than in the D-2 hydrostratigraphic unit; a similar relationship exists between the D-2 and D-1 units.

In summary, figures 26a and 26b show that it is the strength of the groundwater flow system, as measured by hydraulic head loss that controls subsurface temperatures at depths of 300 m (1000 ft) in this area. The clastic rocks of the K-Q hydrostratigraphic unit tend to have a higher hydraulic conductivity than the non-clastic rocks of the D-2 hydrostratigraphic unit (Fig. 22). As a result, K-Q rocks conduct water from the surface faster, so at equal depths, the K-Q unit is cooler than the D-2 unit. The comparison is the same to the D-2 and D-1 hydrostratigraphic units.

Temperatures at depths less than 60 m (200 ft) tend to show an inverse relationship to depth — that is, temperatures decline with depth. Within 60 m of the surface at sites 1, 6, 7, 8, 9, 10, 11, 13, and 17 temperatures decrease with depth. This was also observed by Hume (1947) during drilling in Tp 93, R 10. Parsons (1970) and Lewis and Beck (1977) observed declining temperatures to depth of 50 m and 100 m, respectively in an area of similar climate south of James Bay, Ontario. This phenomenon is thought to be related to strong downward movement of groundwater discussed previously and perhaps to some particularly large recharge event in the past few years. In this area the average temperature at the water table, which is at an average depth of 13 m (43 ft) (Appendix 2), is 6°C, a temperature significantly above the mean annual air temperature of -0.6°C (Fig. 4). This indicates that the mean annual temperature should not be used to approximate temperatures of groundwater in the area. In fact, the temperature of shallow groundwater will reflect the



LEGEND

Boundary of mineable area - 61 m (200 feet) of overburden (modified after Intercontinental Engineering of Alberta Ltd., 1973)

Area 1 - basal McMurray aquifer thicker than 10 m (33 feet), having excellent hydraulic conductivity; high yield wells likely

Area 2 - basal McMurray aquifer 3 to 10 m (10 to 33 feet) thick, having unknown hydraulic conductivity; well yields and spacings expected to be between extremes of areas I and III

Area 3 - basal McMurray aquifer less than 3 m (10 feet) thick, having unknown but presumed low hydraulic conductivity; closely spaced, low yield wells likely

FIGURE 27. Depressurization conditions of the basal McMurray aquifer — mineable area

temperature at the time of major recharge, a temperature not necessarily the mean annual air temperature. Hydrographs from water table wells in the study area indicate that the major recharge event occurs in late April or early May when evapotranspiration is low (Figs. 4 and 5) and an average of about 125 mm (5 in) of winter precipitation is released from the snow pack. Air temperatures at this time average less than 10°C (Figs. 4 and 5) and water temperatures are somewhat lower (Loeppky and Spitzer, 1977). The infiltrating portion of this water, which has a temperature of about 5°C, controls the temperature at the water table.

ENVIRONMENTAL AND TECHNICAL IMPLICATIONS

MINING OPERATIONS

The area currently considered for surface mining operations was defined by Intercontinental Engineering of Alberta (1973) as the area where oil sands underlie less than 200 ft (60 m) of overburden. Hydrogeological problems associated with surface mining in this area are:

1) need for depressurization;
2) possible induced infiltration;
3) poor groundwater quality; and
4) natural gas occurrence.

Need for Depressurization

Both depressurization (the reduction of pore pressure to an accepted level) and dewatering (the removal of pore water) are important to the oil sand mining operations. Depressurization of zones within and just below the oil sands will be necessary to insure pit slope stability and reasonably dry conditions at the bottom of the pit. Dewatering will be necessary only in some surficial materials to facilitate handling.

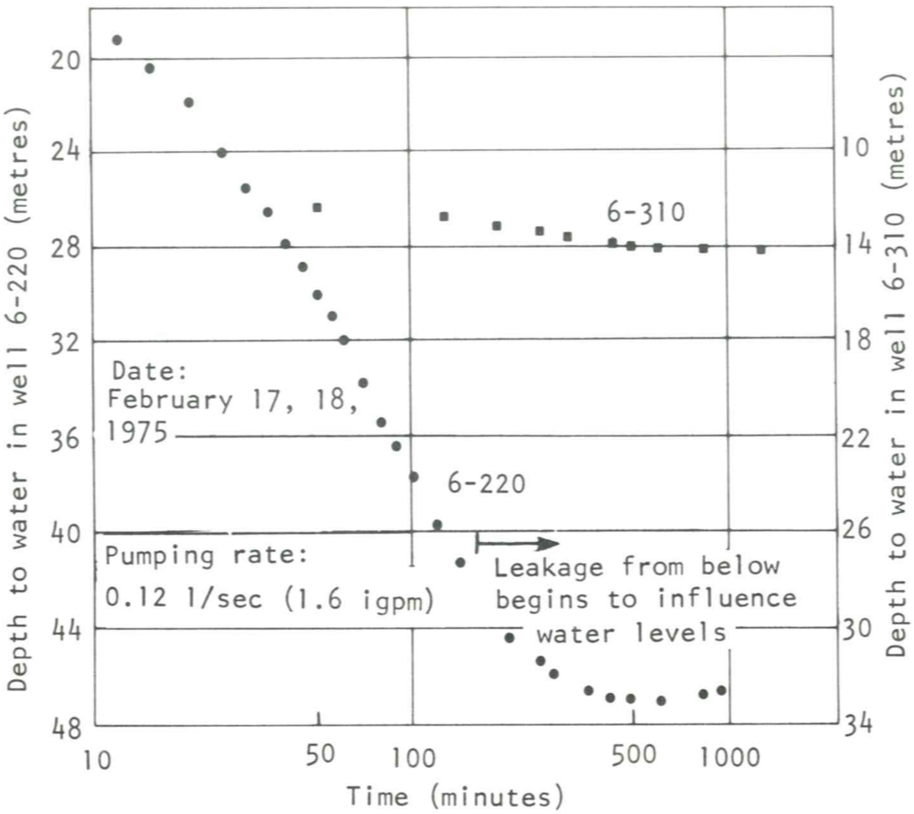


FIGURE 28. Water levels in wells 6-220 and 6-330 during pumping test on 6-220

The design of depressurization systems anywhere in the mining area should be based on pumping tests performed in the manner outlined by Neuman and Witherspoon (1972) for leaky multiple-aquifer systems. Observation wells for analysis of the leaky multiple-aquifer system should be placed in the oil sands, the basal McMurray aquifer, and the Beaverhill Lake Formation. Analyses based upon the assumption that flow in response to pumping takes place only in the McMurray aquifer should be considered suspect for purposes of calculating pumping rates for long-term depressurization. It has already been demonstrated that the vertical hydraulic conductivity of the oil sands is significant, and therefore the pumping of wells may induce flow downward from the oil sands as well as flow upward from the Beaverhill Lake Formation. These extra volumes of water moving into the depressurized area could result in less drawdown than anticipated. The consequences of such a situation could be costly to a mining plan.

Depressurization of the basal McMurray aquifer will generally be required for any mining scheme, since the hydraulic head (Fig. 17b) is typically approximately at the land surface. Data do not permit quantitative evaluations, but qualitative predictions (Fig. 27) of well yields can be made. These predictions are based upon the thickness of the basal McMurray aquifer (Fig. 13) and measured hydraulic conductivity values.

The basal McMurray aquifer is thick and has relatively high hydraulic conductivity in an area under Tps 95, 96, and 97 (Area 1 on Fig. 27). Because of this, depressurization wells can be spaced relatively far apart, but their pumping rates will also have to be quite high.

The basal McMurray aquifer in Area 2 is thinner than in Area 1 and generally has a lower hydraulic conductivity. Depressurization wells will therefore have lower production rates and will need to be spaced closer together. That is, more wells, but producing less individually and in total, will be required to effect a given pressure reduction in the basal McMurray aquifer in Area 2.

In those regions designated as Area 3 (Fig. 27) the basal McMurray aquifer is quite thin and has low transmissivity. Depressurization wells in Area 3 will have to be quite close together and will have very low production rates.

It appears that the Beaverhill Lake Formation may have significant hydraulic conductivity in Tp 95, R 10 as shown by changes in water levels in wells 6-220 and 6-310 (Fig. 28) during a pumping test in well 6-220. The completion zones of these well are about 45 ft (14 m) vertically (Appendix 2) and 50 ft (15 m) horizontally apart. The fact that drawdown occurred in well 6-310 in response to pumping of well 6-220 means that water was moving from the Beaverhill Lake Formation into the McMurray Formation during this test in spite of the 10 ft (3 m) clay layer between these units. The difference in water quality in the two wells (Appendix 2) is evidence against there being a connection along the well bore. The hydraulic connection as indicated by the water level behavior is a natural situation and demonstrates the necessity of applying the Neuman and Witherspoon (1972)

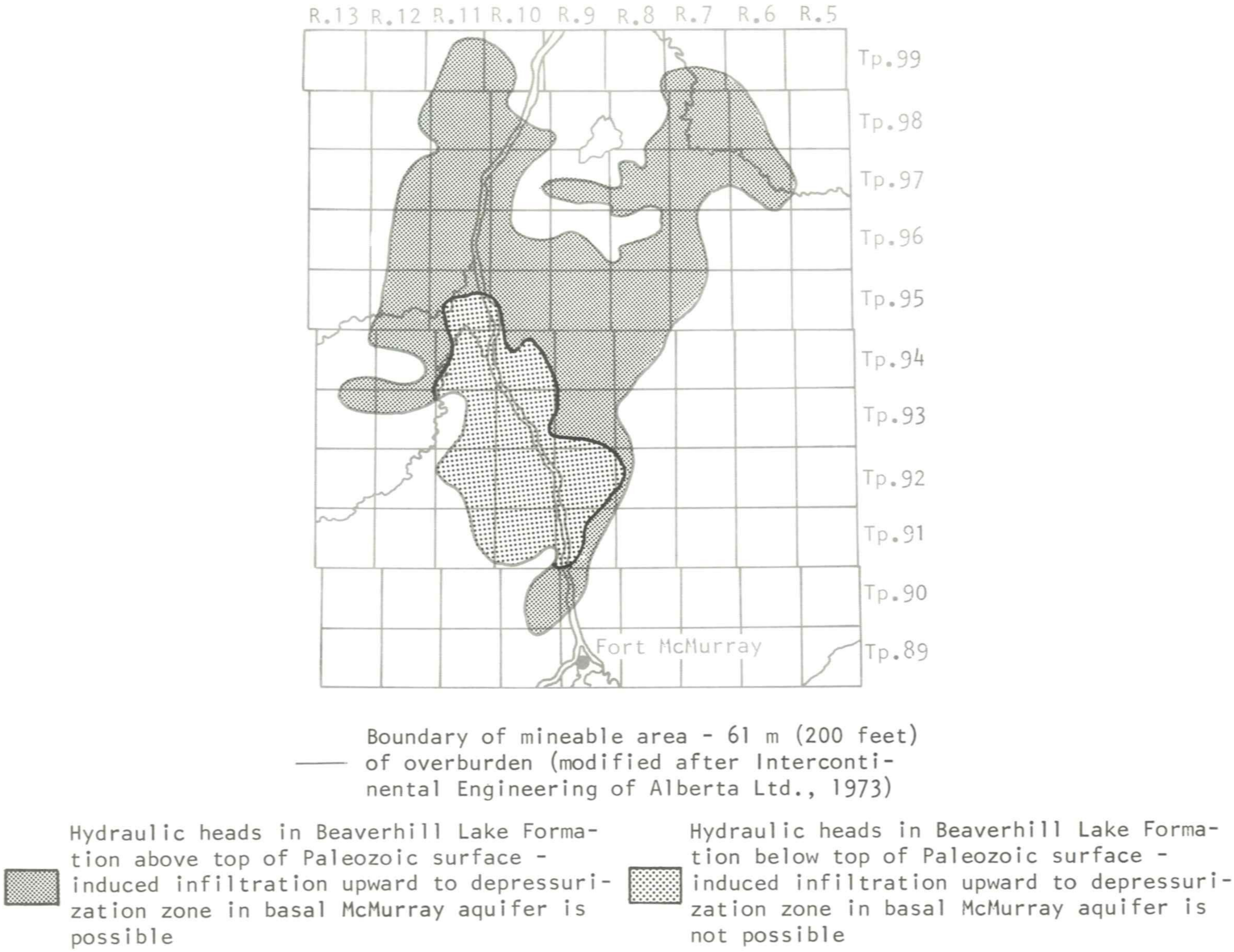


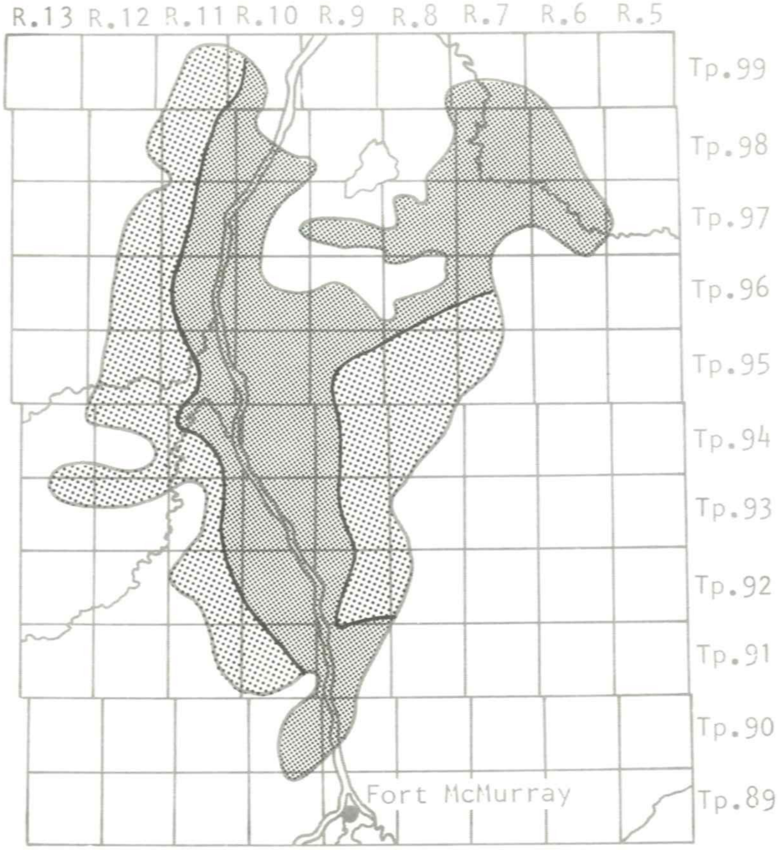
FIGURE 29. Induced infiltration from Beaverhill Lake Formation — mineable area

technique to this area. Evidence indicating the possibility of leakage was also observed during pump tests for Home Oil Company, Tenneco Exploration, and Shell Canada (Hackbarth, 1977). Water probably moves upward from the Beaverhill Lake Formation through fractures caused by collapse of that unit due to solution of the underlying Prairie Evaporite Formation.

Induced flow of groundwater upward from the Beaverhill Lake Formation into the basal McMurray aquifer is not likely to occur in the southwest portion of the mineable area (Fig. 29). In this portion of the study area, the hydraulic head in the Beaverhill Lake Formation (Fig. 17c) is below the surface of the rock unit (Fig. 12), so induced upward flow is not possible.

The basal McMurray aquifer probably will not need depressurizing in any mining operations which start at the river bank and are located in areas where the Paleozoic surface is above the level of the Athabasca River (Fig. 12). Under this combination of circumstances the basal McMurray aquifer is initially drained naturally by being above river level and likely will continue to be adequately drained through the mine pit. The Suncor Inc. mining area typifies this situation: depressurization has not been and likely will not be required to insure slope stability.

Dewatering of overburden materials generally will be necessary, but is not anticipated to be difficult over most of the mining area. Ditches connected to the deeply incised river valleys could drain most of the overburden in the area adequately. In general, areas of eolian, glaciofluvial, or ice contact deposits (Bayrock, 1971; Bayrock and Reimchen, 1973) (Fig. 30) may require more complex overburden dewatering schemes than areas of finer-grained till or lacustrine deposits because the coarser-grained materials cannot be handled easily by dragline or scraper when saturated.



LEGEND

Boundary of mineable area - 61 m (200 feet) of overburden (modified after Intercontinental Engineering of Alberta Ltd., 1973)

Granular glacial deposits at surface; dewatering of surface materials likely to be necessary

Fine-grained glacial deposits at surface; dewatering of surface materials necessary only very locally

FIGURE 30. Overburden dewatering — mineable area

Induced Infiltration from the Athabasca River

Significant amounts of oil sand are situated below the level of the Athabasca River in Tps 95 through 98 (Figs. 12, 14, and 31); induced infiltration from the river in response to depressurization will likely occur in this region. Where the Paleozoic surface is above river level, no induced infiltration is possible.

Boreholes in the Athabasca River reveal sand and gravel deposits up to 49 m (160 ft) thick near Fort MacKay (Table 3). These highly permeable alluvial deposits probably provide a good hydraulic connection between the river and the basal McMurray aquifer. Therefore, it seems likely that induced infiltration from the Athabasca River will occur in this area.

For mining to take place close to the river, hydraulic heads will have to be lowered to an elevation of about 180 m (590 ft) (Fig. 18a) while the river will act as a line source of constant hydraulic head of about 230 m (754 ft). For example, given the known range of hydraulic conductivities and a mine face 1600 m (5248 ft) long, located 1000 m (3280 ft) from the river, between 0.9 and 90 L/sec (12 and 1200 igpm) might be induced to flow through the basal McMurray aquifer into the well system from the river alone. Under such conditions it might prove economical either to pressure-grout the basal aquifer between the mine cut and the river or to construct a clay cut-off wall beneath the pit. Either of these techniques would have the effect of

TABLE 3
Alluvial deposits along the Athabasca River

Location	Thickness of alluvial deposits (m) [1]	Lithology
NW-29-93-10	49	sand, gravel, clay
SW-7-94-10	29	sand, gravel
NE-25-94-11	34	sand, gravel
SE-25-94-11	43	sand, gravel

[1] Maximum thicknesses encountered measured relative to river level.

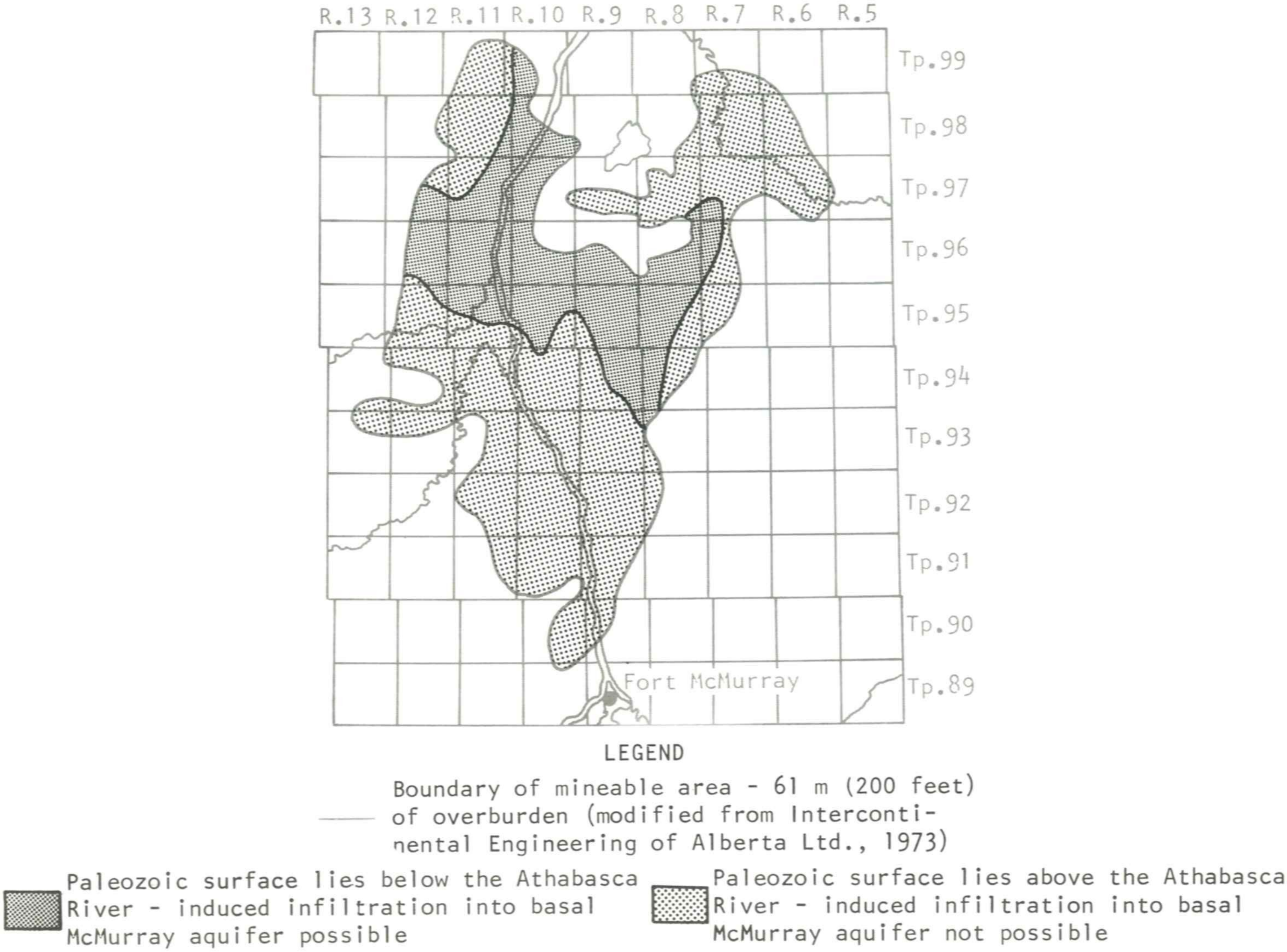


FIGURE 31. Induced infiltration into basal McMurray aquifer from the Athabasca River — mineable area

reducing the amount of induced infiltration. The cost of these measures, amortized over the life of the mine, might be offset by the decreased pumping costs.

Several hydrogeological factors might be considered when the suitability of a grout curtain or cut-off wall to reduce induced infiltration is evaluated.

1) Some induced infiltration from the river could be beneficial, as it would dilute the concentration of salts in the pumped water. This would be particularly important if significant volumes of poor quality water were to move upward from the Beaverhill Lake Formation (Fig. 29) into the basal McMurray aquifer. It could be desirable, therefore, to close off the aquifer only partially, thus allowing some induced infiltration.
2) The existence of the grout or cut-off wall could cause groundwater problems after mining operations cease. Under natural conditions water moves through the basal McMurray aquifer and discharges into the Athabasca River. The grout curtain or cut-off wall would retard this movement and would force the water upward to the surface and downward into the Beaverhill Lake Formation. Upward-moving water would travel through spoil materials in the abandoned pit. Water discharged in this manner would carry with it salts and chemicals contained in the pit as well as cause waterlogging of the surface. Both of these conditions would hinder reclamation efforts. Downward flow of water around the grout curtain is not anticipated to be detrimental.

The long-term effects of induced infiltration and mitigating measures should be studied carefully at any early stage in mine planning.

Poor Water Quality

The water produced by depressurization wells in the basal McMurray aquifer is expected to have total dissolved solids and chloride ion concentrations of less than 10,000 mg/L and 5,000 mg/L, respectively, except in the northwest (Tps 95 to 97 and Rs 10 to 12) (Fig. 23c). Lesser concentrations will be more prevalent in the northeast portion of the mineable area.

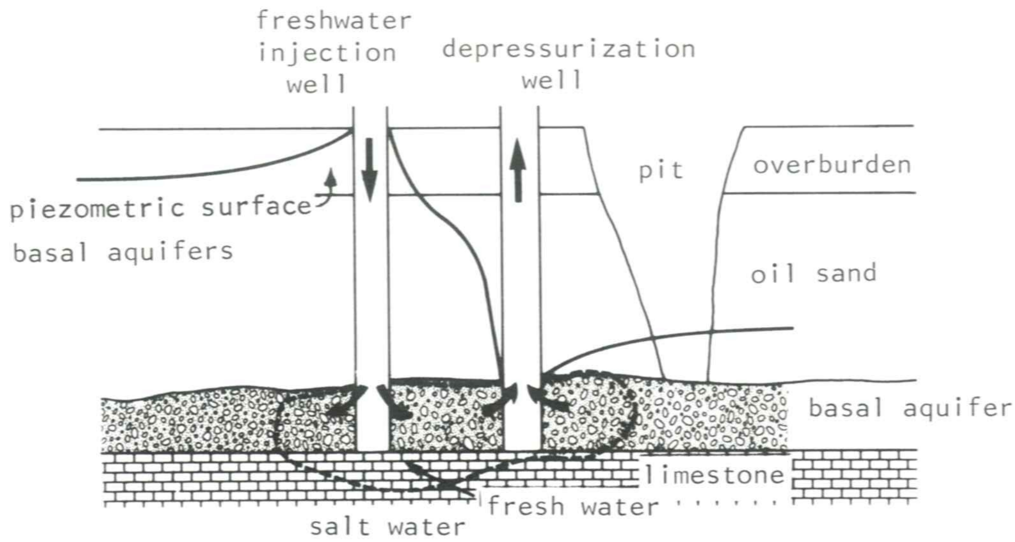


FIGURE 32. Pressure ridge method of salt water control

Total dissolved solids concentration of groundwater flowing from the Beaverhill Lake Formation to the basal McMurray aquifer due to depressurization is expected to be less than 50,000 mg/L everywhere except in the northwest area. Chloride ion is anticipated to be less than 10,000 mg/L. Thus, the water in the basal McMurray aquifer would be degraded in quality if mixed with water from the Beaverhill Lake Formation. Current information is not adequate to determine whether, in fact, large volumes of water would move upward from the Beaverhill Lake Formation in response to pumping in the basal McMurray aquifer. Developers, particularly those who intend to mine in the northeastern area, should investigate this possibility early in the planning stage.

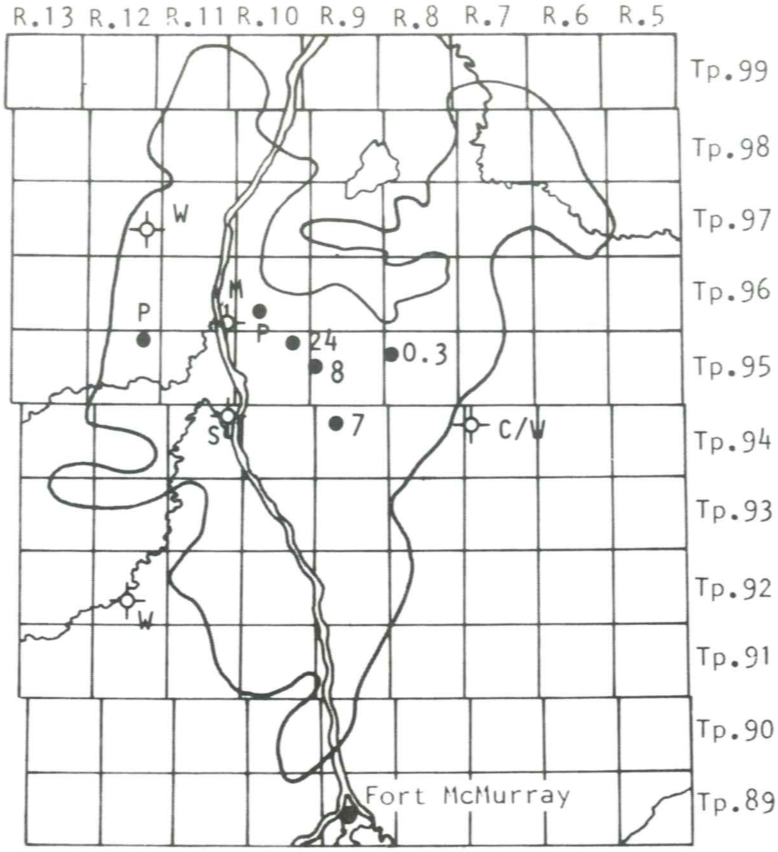
The quality of water in the McMurray and Beaverhill Lake Formation is extremely poor in the northwest portion of the mineable area; total dissolved solids concentrations in excess of 100,000 and 200,000 mg/L are predicted for these formations, respectively. Also relatively large volumes of water will have to be pumped from the basal McMurray aquifer (Fig. 27) in order to effect depressurization. This combination of relatively high hydraulic conductivity and poor quality, along with the possibility of upward leakage of even poorer quality water from the Beaverhill Lake Formation, make it unlikely that the pumped water could be released into surface water bodies for disposal by dilution. The smaller streams of the area (Pierre River, Calumet River, Eymundson Creek, and Tar River) commonly freeze completely to the bottom (Table 1) during very cold portions of the winter, so any pumped water released into them would constitute nearly all of the flow during that season. The Ells River has a winter flow rate of only about 1.4 m^3/sec (50 ft^3/s) (Table 1), so the addition of even several tenths of a cubic metre per second of pumped water would seriously degrade water quality in this river.

Subsurface control of salt water — Three methods for control or disposal of the pumped salt water are discussed in this report: 1) subsurface injection, 2) pressure ridge method, and 3) controlled infiltration of water from the Athabasca River. One or more of these techniques should be evaluated in detail prior to mining in this area. Desalinization of the pumped water will not be discussed because it is a well-known technology and its application to this problem is one of economics rather than hydrogeology.

The pressure ridge method (Todd, 1959; Sheahan, 1977) for control of salt water intrusion has been used successfully, at various locations and the possibility of using it in this area should be considered. The method involves the injection of freshwater into an aquifer to cut off a source of undesirable water. Its application to oil sands depressurization is presented schematically in figure 32. The objective of the scheme is to produce water of low total dissolved solids content which can either be reinjected or released into surface water. Utilization of the technique would involve a detailed hydrogeological feasibility study, as well as an economic assessment of the various alternatives for disposal or storage of the saline water.

Another procedure which should be considered is to allow induced infiltration of water from the Athabasca River rather than to prevent it with cut-off walls or by grouting. Infiltrating water from the Athabasca River will have a total dissolved solids content of about 100 to 300 mg/L. Thus, for example, mixing of one part of river water with one part of water from the basal McMurray aquifer having 100,000 mg/L total dissolved solids would result in produced water having about 50,000 mg/L. If significant volumes were induced to flow from the Athabasca River to the pumping wells, mixing could possibly reduce the concentration of total dissolved solids in the water produced to a level suitable for release into surface environments.

A detailed economic analysis of the alternatives of 1) pumping and surface treatment, 2) pressure injection of freshwater, or 3) induced infiltration and mixing for water quality maintenance should be conducted before mining proceeds in this area.



LEGEND

—— Boundary of mineable area - 61 m (200 feet) of overburden (modified from Interconti-nental Engineering of Alberta Ltd., 1973)

● 8 H_2S produced from basal McMurray aquifer; concentration in water in Mg/l

● P H_2S produced from basal McMurray aquifer; noticeable amount

⌖ W Sweet natural gas produced during pump test or without pumping
W - Wabiskaw Member
M - McMurray Formation
C - Clearwater Formation
S - Slave Point/Watt Mountain Formations

FIGURE 33. Observed occurrences of natural gas — mineable area

Natural Gas Occurrences

Natural gas will be produced in portions of the mineable area in conjunction with depressurization activities. The locations of Alberta Research Council wells observed to produce natural gas are shown in figure 33.

Hydrogen sulfide has been observed in the water produced during some pumping tests, and its presence may be linked to greater thicknesses of the basal McMurray aquifer (Figs. 13 and 27). Thus, relatively high concentrations of hydrogen sulfide likely would develop where large volumes of water must be pumped from the basal McMurray aquifer. Consideration of the safety aspects of pumping water containing hydrogen sulfide gas is beyond the scope of this report. Special equipment likely would be necessary to collect the gas and flare it at the well-head in order to insure the safety of personnel. Rates of hydrogen sulfide and sulfur dioxide production (from flaring) for various pumping rates and hydrogen sulfide concentrations are presented in figure 34. The calculations to produce this figure are based on the assumption that complete combustion of hydrogen sulfide by flaring to produce sulfur dioxide would take place.

Dissolved gases can present problems for a depressurization system in two ways:

1) As the hydraulic head is lowered, gas could come out of solution in the aquifer and act to reduce its hydraulic conductivity. This situation has been observed at the Syncrude site (Nichols, 1975).
2) Large gas bubbles within the well bore could cause cavitation and related problems with pumps.

Natural gas in the Wabiskaw Member of the Clearwater Formation could present occasional problems during removal of overburden. Three locations in and near the mineable area where gas has been observed in the

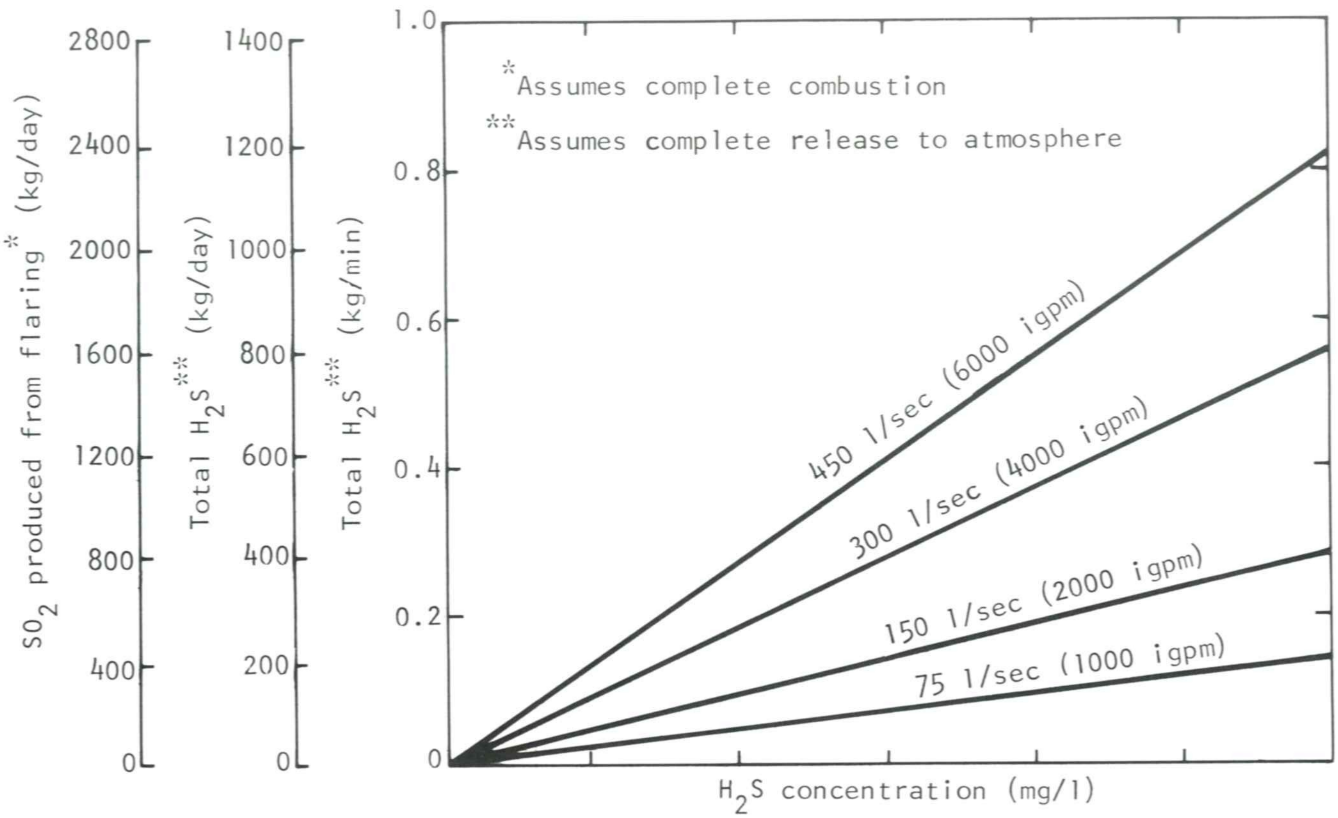


FIGURE 34. Hydrogen sulfide and sulfur dioxide production from pumping wells

Wabiskaw Member are shown in figure 33. The volumes of gas flow at the three sites are not significant: pressures, calculated from the hydraulic head in the wells, are less than 172 kpa (25 psi). Occurrences of gas appear to be limited to the outer portion of the mineable area where significant thickness of shale or other overburden overlie the Wabiskaw Member.

Gas in the Slave Point or Watt Mountain Formation has been reported at one location at Fort MacKay. A blow-out of "sweet" gas occurred at a depth of about 130 m (425 ft) during the drilling of a hole in Lsd 11, Sec 25, Tp 94, R 11. Natural gas in the McMurray Formation has been reported in Tp 95, Rs 15, 16 and 17 just to the west of the mineable area.

IN SITU OPERATIONS

The environmental and technical impact of regional groundwater flow patterns on in situ operations is much less understood than their impact on mining operations. This is due partly to the fact that in situ technology is in its infancy and is not as well understood as mining technology, and partly to the fact that the process is out of sight and cannot be observed as it takes place.

Virtually all in situ technology under serious consideration involves the application of heat to reduce viscosity and high pressures to produce the oil. The high pressures would result in flow of fluids away from the injection zones with the magnitude of this flow dependent on the permeability of the surrounding materials. The presence of a continuous clay layer of adequate thickness on the top of the Paleozoic surface would seem to be necessary to minimize flow of fluid from the injection zones into the Beaverhill Lake Formation where pressures are generally much lower (Fig 17c). Particularly detailed investigations of the continuity of the clay layer should be carried out in those areas where solution of the Prairie Evaporite Formation has resulted in collapse of the Paleozoic surface (Fig. 12). It was demonstrated previously that groundwater could be induced to flow from the Beaverhill Lake Formation into the McMurray Formation in response to pumping. Movement in the reverse direction could just as easily take place due to pressure increases used for in situ production. An assessment of the degree of hydraulic connection between the McMurray Formation and the Beaverhill Lake Formation is an essential part of any in situ project.

There are currently five in situ techniques under serious consideration for recovery of bitumen from oil sands (D. A. Redford, Alberta Research Council, pers. comm.):

1) single-well steam stimulation
2) interwell steam stimulation
3) combustive heating

4) electric heating
5) underground mining.

Hydrogeological factors related to each of these are discussed separately.

Single-Well Steam Stimulation
This is a single-well process in which the oil sands are alternately heated and pumped. Pressures greater than those necessary for fracturing are commonly used to ensure sufficient penetration of the steam into the reservoir during the heating phase. After a period of time the high pressure injection of steam is stopped and the well is allowed to flow producing a mixture of hot water, steam, and oil. When production drops below a selected volume, high pressure steam is again applied.

Towson (1976) noted that significant heat losses can occur if an aquifer is intersected by the steam injection zone because the injected fluids would tend to move into that zone carrying heat with them. Any chemicals added to the steam would also enter the aquifer.

Induced fracturing should be done with care in those areas influenced by solution of the Prairie Evaporite Formation. Particular caution is advised in the immediate vicinity of the Sewetakun Fault as collapse features associated with it do affect the McMurray Formation (Figs. 12 and 14). Uncontrollable losses of steam could occur through the fault or associated collapse features. The local role of the fault should be evaluated prior to development.

Care should be taken to insure that the induced fracturing is basically horizontal. Vertical fractures would destroy the effectiveness of overlying and underlying confining layers. Dusseault (1977b) suggested that the natural state of stress in the oil sands in the area is such that induced fractures would be horizontal at depths shallower than about 300 to 460 m (about 1000 to 1500 ft) and vertical at greater depths. It would appear, therefore, that vertical fractures could be induced during in situ operations in a significant portion of the deposit.

Interwell Steam Stimulation
This is a multiwell process in which steam is injected at a central well and recovery of heated oil takes place at surrounding wells. The injection well and the withdrawal wells may be developed for steam and oil movement either through induced fractures or through naturally permeable zones. Once the viscosity of the oil in the reservoir has been reduced by heating, the withdrawal wells are opened to produce an oil and water mixture.

The concerns expressed for single well stimulation regarding fracturing apply to this technique also.

Using a naturally permeable zone to connect the injection and withdrawal wells is cause for concern. The use of such a zone would not only facilitate heating of the reservoir but by its very nature will also lead to loss of some of the injected fluids. A portion of the chemicals injected to facilitate the oil recovery process would be carried away from the injection area by water moving through the permeable zone and would not be recovered by the withdrawal wells. Because of the downward hydraulic gradients prevalent in the area, some of the injected substances would be carried into the Beaverhill Lake Formation and ultimately into the Athabasca or Clearwater Rivers.

Combustive Heating
This is another multiwell process in which the oil sands are fractured by high pressure air and subsequently ignited. Combustion takes place along horizontal fracture planes away from a central well toward surrounding withdrawal wells. Several fracturing phases may be required in order to heat a large enough portion of the reservoir between the wells; as well, it could be necessary to choke or shut-in the withdrawal wells during these fracturing periods in order to build up pressure in the reservoir to maintain open fractures or create new ones. After the reservoir is sufficiently heated, the withdrawal wells are opened and allowed to flow. The next phase calls for the ignition of the oil at the central well and the injection of an air and water mixture at a pressure below that which would cause fracturing. This process produces stream in situ and forces the oil towards the withdrawal wells.

Fracturing is important during the initial phases of this technique and therefore all of the concerns expressed previously apply.

The underground combustion process produces sulfur dioxide, hydrogen sulfide, and carbon monoxide gases (Redford, 1976). Some of these gases would dissolve in the local groundwater and move away from the injection zone. The sulfur dioxide and hydrogen sulfide would react with the water, if enough oxygen were available, to produce sulfuric acid which in turn would react with the limestones or calcareous basal McMurray clays. This would cause an increase in the concentrations of calcium, magnesium, carbonate, and bicarbonate ions in the groundwater. This reaction could enhance the secondary permeability of these units leading to decreased pressures.

If the oxygen present was insufficient to produce sulfuric acid, the sulfur dioxide and hydrogen sulfide would move with the groundwater to a discharge area. Upon discharge sufficient oxygen would be available to convert these compounds to sulfuric acid. Efforts should be made to examine the magnitude of this problem prior to large scale operations.

Water-soluble organic acids are also produced by the combustion process (D. A. Redford, Alberta Research Council, pers. comm.). The amounts produced and the reactions which they could cause are a matter of conjecture at present, but such compounds could cause environmental problems if released into surface water.

Companies proposing to locate recovery projects in areas where collapse features are evident on the Paleozoic surface (Fig. 12) should carefully examine the details of that surface in their lease area. Fractures and collapse features probably affect the McMurray Formation as well as the Paleozoic rocks and could result in the loss of necessary driving pressures. Significant amounts of combustion products and oil could be lost to the underlying Beaverhill Lake Formation.

Electric Heating

In this technique the temperature of the reservoir is raised by the heat generated from the resistance of the rocks to the flow of an electric current. Once an acceptable reservoir temperature is obtained, the oil is forced toward withdrawal wells by relatively low-pressure injection of steam.

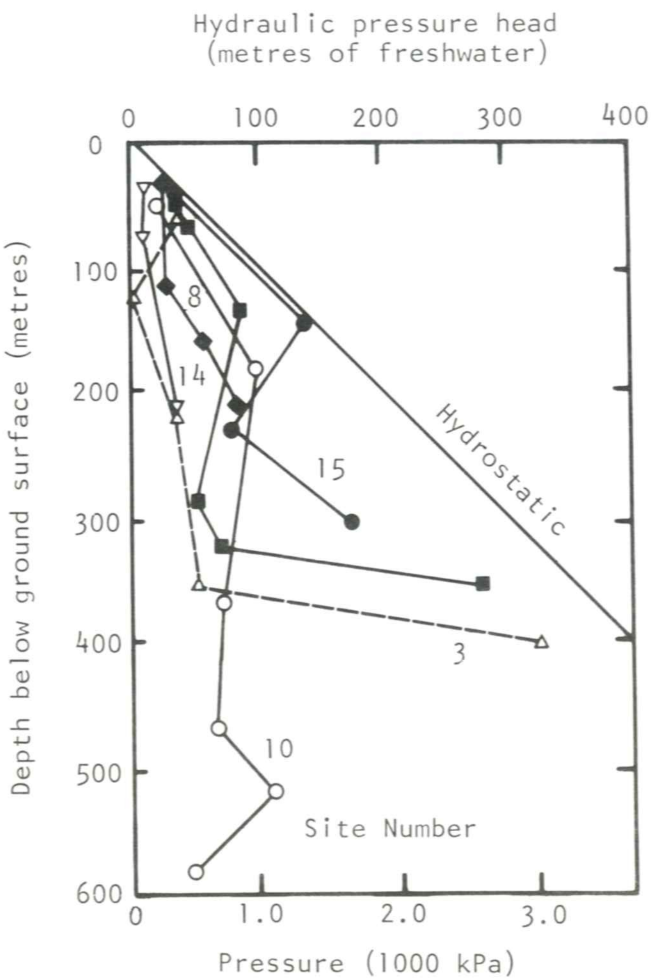


FIGURE 35. Hydraulic head versus depth of observation — in situ area

The low steam pressure would not cause fracturing of the reservoir, so escape of fluids by that means to surrounding works would not be a problem. Migration of fluids away from the injection area could still take place under the increased pressures, and detailed investigations will be necessary to determine the volumes involved.

Underground Mining

Bernshtein *et al.* (1973) described a modification of the steam stimulation method used in the Soviet Union. This technique involves constructing tunnels within or adjacent to the reservoir and drilling holes from these tunnels into the reservoir for single-well steam stimulation. Currently there is interest in constructing tunnels within the Beaverhill Lake Formation followed by upward drilling for steam injection. (R. Brimhall, Resources Sciences Corp., pers. comm.). The concerns expressed previously about fracturing and fluid migration in techniques involving application of high pressure apply to this method also.

Tunnels constructed in the Beaverhill Lake Formation would experience pressures much less than hydrostatic, particularly near the Sewetakun Fault (Figs. 17 and 18). There is, however, the distinct possibility that the strength of the limestone would be reduced due to collapse features (Mossop, 1978) and faulting. Access shafts would have low hydraulic pressures in most areas due to the strong downward hydraulic gradients. Hydraulic pressures would be less than hydrostatic as shown in figure 35. It appears that high hydraulic pressures would not present a problem to shaft construction in most areas. Further discussion of hydrogeological concerns in underground excavation is presented in Hackbarth (1978b).

Hydraulic mining, either from the surface or from tunnels driven beneath the oil sand, has been considered (D. A. Redford, Alberta Research Council, pers. comm.). The technique calls for high pressure jetting of the oil sands with water through holes drilled with conventional drilling equipment. The oil sand would be eroded by the jet and would return to the point of drilling with the flow of water.

The large volumes of water necessary for this method likely would not be available from groundwater and would have to be supplied from surface water. Substantial volumes of make-up water would be necessary also because of hydraulic heads created would force water out of the jetting zone. A basal McMurray aquifer with significant hydraulic conductivity could take large volumes of water.

Nuclear Detonation

Proposals have been brought forward since 1959 for the use of nuclear explosions to extract oil from the Athabasca Oil Sands (Anonymous, 1959; Alberta Technical Committee, 1959; Natland, 1963). The proposals call for detonation of the device in the Beaverhill Lake Formation below the oil sands and envisage creation of a cavity into which the oil sands would collapse. The heat released would reduce the viscosity of the oil allowing production by conventional petroleum recovery methods. The technique is not under serious consideration at present due to the many problems anticipated with the resultant radioactive products.

It is not within the scope of this publication to evaluate the hydrogeological implications of subsurface nuclear detonation. The investigation relating to the Nevada Test Site (Eckel, 1968) of the United States Atomic Energy Commission should provide useful principles from which to begin any investigations.

SUBSURFACE WASTE INJECTION

The following statements on wastewater injection in the study area are based on many of the recommendations expressed by van Everdingen and Freeze (1971) and van Everdingen (1974a, 1974b). These comments are general in nature due to the lack of information on the quality and quantity of waste waters produced from bitumen-upgrading processes.

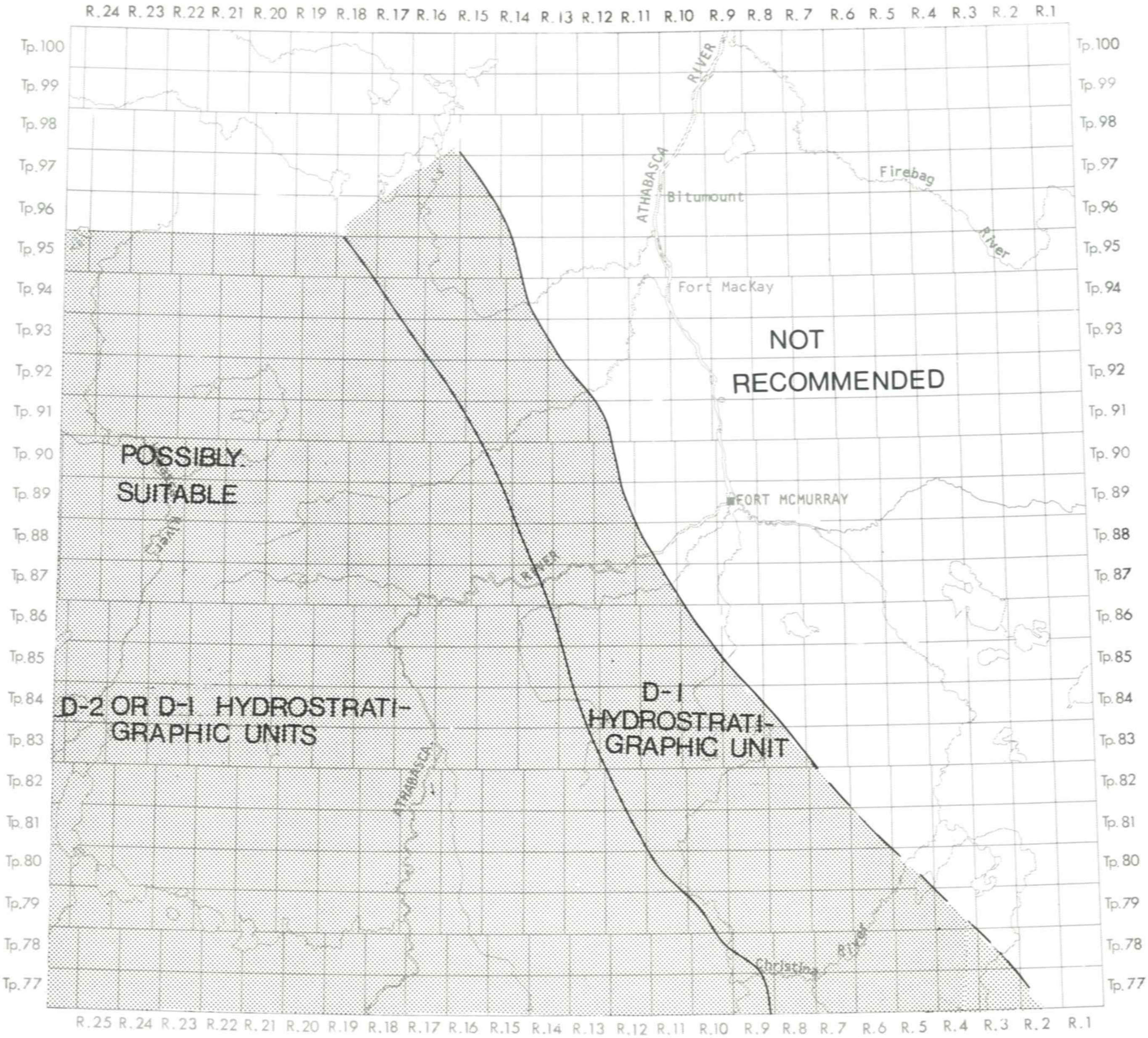


FIGURE 36. Suitability for liquid waste injection

Structural and stratigraphic factors determine whether or not overlying layers can effectively confine waste fluids injected into a given unit. On this basis, the study area can be considered as having possibly suitable to unsuitable conditions for subsurface injection of liquid waste (Fig. 36). Injection should be limited to fluids that cannot be disposed of by any other means.

The study area can be divided into three regions (Fig. 36) based on suitability for subsurface injection. Generally, the structural and stratigraphic conditions make the northeastern half of the area, including all of the surface-mineable area, unsuitable for waste injection into any formation. The southwestern half of the area has potentially suitable stratigraphy and structure to allow injection into the D-1 hydrostratigraphic unit in the east and into both the D-2 and D-1 hydrostratigraphic units in the west.

The area indicated as unsuitable for waste injection was so defined because the Prairie Evaporite and Beaverhill Lake Formations are probably unsatisfactory confining layers above an injection zone in the D-1 hydrostratigraphic unit. As discussed previously, the Sewetakun Fault may have affected rocks at least as young as Devonian age and has also lead to enhanced salt solution in the Prairie Evaporite Formation which contributed to collapse of parts of the Beaverhill Lake and McMurray Formations. These conditions call into question the ability of both the Prairie Evaporite and the Beaverhill Lake Formations to act as confining layers for injected liquids. The possibility of rapid upward movement of injected liquids through the faulted and collapsed zones to the Athabasca or Clearwater Rivers is quite great.

Also, the Prairie Evaporite Formation is essentially absent east of the Sewetakun Fault (Fig. 18a). This situation and the presence of karst features in the Beaverhill Lake Formation in the same area (Fig. 12) add to the unsuitability for liquid waste injection.

Hydraulic heads in the D-1 hydrostratigraphic unit are at or above land surface over most of the area west of the Sewetakun Fault (Fig. 17d). In order to inject significant volumes of liquid against these heads and with hydraulic conductivities such as those indicated on figure 22, pressures in excess of lithostatic may be necessary. This condition will result in hydraulic fracturing — a situation to be avoided (van Everdingen, 1974a). Vertical fractures could quite easily traverse the already thin Prairie Evaporite Formation and affect the Beaverhill Lake Formation, thus creating pathways for liquid movement into a system known to be connected to the surface. Horizontal fracturing would not remedy the situation because such fractures could intersect with the fault, providing an upward connection.

Aside from the problems of hydraulic fracturing, the large increases in pressure needed for injection might augment flow in natural salt springs or even create new springs. Natural salt springs now discharge water that is a mixture of water from both shallow and deep flow systems. An increase in hydraulic head in the deeper systems would mean that a larger proportion of the mixture would be water from this source and consequently the springs would not only increase in flow but also discharge more saline water.

The area noted in figure 36 as possibly suitable for waste injection has been divided into two subregions based upon potential receiving formations.

Waste injection into the D-1 hydrostratigraphic unit is regarded as feasible only west of the line which coincides with the influence of salt solution on the Prairie Evaporite Formation. East of the line, as stated previously, it is likely that overlying units have been disturbed. West of the line the unit has very high total dissolved solids content (Fig. 23e), is deeply buried (Fig. 10), and has a very impermeable upper confining layer (the Prairie Evaporite Formation); all of these features make it acceptable as an injection unit. Possible limitations may be the low hydraulic conductivity (Fig. 22) and high hydraulic heads (Fig. 17d); however, these might be overcome through hydraulic fracturing.

Waste injection into the Beaverhill Lake Formation, particularly its lower portions, may be acceptable in the southwestern half of the area. In this region the Upper Devonian is thickened by the onlap of the Woodbend Group and is deeply buried because of the regional dip (Fig. 18b). The quality of water in the Beaverhill Lake Formation (Fig. 23d) is much better than in the D-1 hydrostratigraphic unit (Fig. 23e), but is still less than desirable for most uses. Low hydraulic heads (Figs. 17c and 18b) mean that gravity flow through the injection well may be possible if zones of sufficient hydraulic conductivity can be located. Because of an apparently low hydraulic conductivity, it may be necessary to resort to fracturing in order to inject large volumes of liquid. Injection wells should be properly sealed and completed far enough below the oil sands to preclude migration of waste to those deposits.

MUNICIPAL AND INDUSTRIAL WATER SUPPLIES

It is unlikely that groundwater of suitable quantity and quality for municipal purposes is present in the study area. The maps of total dissolved solids concentration (Fig. 23) indicate that the only unit having water of suitable quality is the Grand Rapids Formation. This unit also has high hydraulic conductivity (Fig. 22). At most locations the major problems in wells would be large pumping lifts — meaning high pumping costs — and low available drawdown — meaning restricted pumping rates. Thus, surface waters will probably have to be the source of municipal supplies.

Locally, glacial drift, due to its apparently high hydraulic conductivity, (Fig. 22) may yield enough water to support small industrial operations such as pilot plants. As the lithology of the drift is highly variable, detailed studies are required to ensure that supplies will be adequate for the time period over which they are needed.

The possible sources of groundwater for industrial purposes are the same as for municipal supplies. According to Bouthillier (1972), about 10 million gallons of water per day (38,000 m^3/day) will be required for refining alone in a 100,000 barrels per day (16,000 m^3/day) extraction plant. Additional water would be needed for make-up water in the hot water separation process or for boiler feed for in situ operations. This volume of water is probably not available from groundwater sources except possibly from the basal McMurray aquifer inTps 95 to 97 Rs 8 to 12 (Fig. 13). At all other locations there are not aquifers identified that might yield this volume of water. Furthermore, the quality of water likely would be too poor for even low-pressure boilers (Todd, 1970).

It is anticipated that surface waters will be the source of virtually all the municipal and industrial supplies required in the area.

SUMMARY

1) The geology of the area consists of Holocene sediments and Cretaceous clastic rocks unconformably overlying Devonian strata which in turn overlie Precambrian metasedimentary rocks. Regional dip is toward the southwest at about 25 ft/mi (4.8 m/km) in the Devonian and at about 8 ft/mi (1.5 m/km) in the Cretaceous.

2) A major fault, named the Sewetakun Fault, trends north-northwest and passes under Fort McMurray. Vertical displacement on this fault appears to be about 273 ft (83 m); the fault is likely to have affected rocks of age as young as Late Devonian. The fault has enhanced solution of the salts of the Prairie Evaporite Formation within about 16 km (10 mi) on the western side and for an unknown distance to the east. Collapse features are noted in all formations overlying the area of solution of the Prairie Evaporite Formation.

3) Three hydrostratigraphic units are defined west of the Sewetakun Fault:

   The K-Q hydrostratigraphic unit consists of the Holocene and Cretaceous rock units. It is characterized by good quality water and dominantly vertical groundwater flow interrupted by horizontal flow in the very permeable units.

The D-2 hydrostratigraphic unit consists of all Devonian rock units above the Elk Point Group. Groundwater flow in this unit is dominantly horizontal towards the northeast. A zone of hydraulic heads approximately equal to the levels of the Athabasca or Clearwater Rivers is observed to parallel the Sewetakun Fault and is hypothesized to be due to secondary hydraulic conductivity originating from fracturing and collapse.

The D-1 hydrostratigraphic unit includes all rock units below the Prairie Evaporite. This unit is characterized by hydraulic heads at or above ground surface and by concentrations of dissolved solids in excess of 200,000 mg/L. Groundwater flow in this unit is toward the northeast. A zone of relatively low hydraulic heads paralleling the Sewetakun Fault is observed in this unit also.

The D-1 and D-2 hydrostratigraphic units merge east of the Sewetakun Fault.

4) Considered on a regional scale, the oil sands are permeable to water. Hydraulic conductivities of 10^{-6} to 10^{-4} cm/sec are expected to be common.

5) Depressurization of the oil sands and the immediately underlying basal McMurray aquifer will generally be necessary for surface mining to take place. South of Tp 94 mining operations commencing at a deeply incised river valley may not require depressurization wells. Due to the substantial thickness (greater than 30 ft (12 m)) and the excellent hydraulic conductivity of the basal McMurray aquifer, large volumes of water will have to be pumped to effect depressurization in portions of Tp 95 to 97, Rs 8 to 12; concentrations of hydrogen sulfide gas in this water may be sufficient to require special attention.

   Induced infiltration from the Athabasca River to depressurization wells may occur near the Bitumount Basin. Economics may warrant procedures designed to reduce the amount of infiltration.

   Depressurization wells near the Tar River will produce water having total dissolved solids concentration greater than 100,000 mg/L. Special consideration will have to be given to disposal of the water, as direct release to surface environments may not be acceptable.

6) Before establishing in situ operations in those areas where solution of the Prairie Evaporite Formation has taken place, developers should carefully examine the geological structure. Faults and collapse features may have affected the oil sands sufficiently to cause loss of production pressures and injected fluids.

7. Subsurface injection of liquid wastes is not recommended east of a line which generally corresponds with the first observable indication of evaporite solution. Structural conditions are suitable for injection of liquids into the D-1 hydrostratigraphic unit west of this line, but permeability and hydraulic heads will have to be examined at the specific site in question. Liquid waste injection into the Beaverhill Lake Formation may be possible where the overlying Woodbend Group is sufficiently thick.

8) Groundwaters are inadequate, in terms of both quality and quantity, for use as industrial or municipal supplies anywhere in the area.

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APPENDIX 1.

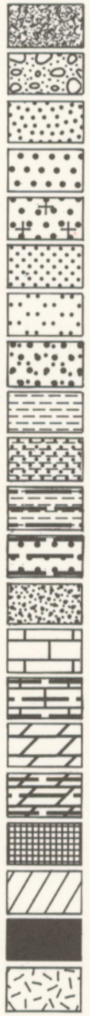
LOCATIONS, ELEVATIONS, AND COMPLETION FORMATIONS OF OBSERVATION WELLS

Site Number	Well Name	Completion Formation	Location (W 4th)	Elevation (m)	Elevation (ft)
1	1 - 32	Drift	Lsd 8-15-96-11	259	850
	1 - 123	McMurray			
	1 - 432	McMurray			
	1 - 507	Beaverhill Lake			
	1 - 726	Prairie Evaporite			
	1 - 1040	La Loche			
2	2 - 46	Drift	Lsd 1-11-97-12	323	1059
	2 - 222	Clearwater			
	2 - 402	McMurray			
	2 - 525	Beaverhill Lake			
3	3 - 44	Drift	Lsd 9-26-97-13	613	2012
	3 - 57	Dunvegan			
	3 - 209	Shaftesbury			
	3 - 425	Grand Rapids			
	3 - 731	Grand Rapids			
	3 - 1144	McMurray			
	3 - 1310	Beaverhill Lake			
6	6 - 21	McMurray	Lsd 2-18-95-9	300	985
	6 - 220	McMurray			
	6 - 310	Beaverhill Lake			
7	7 - 32	Clearwater	Lsd 13-20-95-8	326	1071
	7 - 135	McMurray			
	7 - 337	McMurray			
	7 - 594	Prairie Evaporite			
	7 - 933	La Loche			
8	8 - 34	Drift	Lsd 5-30-94-7	430	1412
	8 - 114	Drift			
	8 - 220	Clearwater			
	8 - 370	McMurray			
	8 - 532	Beaverhill Lake			
	8 - 716	Beaverhill Lake			
9	9 - 43	Drift	Lsd 16-4-94-6	615	2018
	9 - 161	Drift			
	9 - 449	Drift			
	9 - 951	McMurray			
	9 - 1056	McMurray			
	9 - 1150	Beaverhill Lake			
10	10 - 47	Drift	Lsd 9-25-85-9	764	2505
	10 - 165	Drift			
	10 - 592	Drift			
	10 - 1215	Grand Rapids			
	10 - 1530	McMurray			
	10 - 1700	McMurray			
	10 - 1905	Beaverhill Lake			
11	11 - 33	Drift	Lsd 16-2-87-9		
	11 - 130	Grand Rapids			
	11 - 460	McMurray			
	11 - 595	McMurray			
	11 - 920	Beaverhill Lake			
12	12 - 115	Drift	Lsd 8-27-88-0	372	1221
	12 - 270	McMurray			
	12 - 460	McMurray			
	12 - 1092	Prairie Evaporite			
13	13 - 70	Drift	Lsd 8-11-90-12		
	13 - 230	Drift			
	13 - 460	Grand Rapids			
	13 - 770	McMurray			
	13 - 872	McMurray			
	13 - 1230	Beaverhill Lake			

APPENDIX 1. (CONTINUED)

Site Number	Well Name	Completion Formation	Location (W 4th)	Elevation (m)	Elevation (ft)
14	14 - 31	Drift	Lsd 4-15-92-12	373	1223
	14 - 119	Clearwater			
	14 - 247	McMurray			
	14 - 699	Beaverhill Lake			
	14 -1590	Methy			
15	15 - 53	Drift	Lsd 15-33-89-16	480	1575
	15 - 135	Drift			
	15 - 477	Clearwater			
	15 - 750	McMurray			
	15 - 997	Beaverhill Lake			
16	16 - 55	Drift	Lsd 13-90-10	342	1122
	16 - 165	Wabiskaw-McMurray (?)			
	16 - 325	McMurray			
	16 - 550	Beaverhill Lake			
17	17 - 45	McMurray	Lsd 13-12-94-11	262	861
	17 - 200	Beaverhill Lake			
-	BP-1W	Beaverhill Lake	Lsd 15-3-96-11	273	895
-	BP-2W	Beaverhill Lake	Lsd 14-36-95-12	316	1038
-	BP-2WA	McMurray	Lsd 14-36-95-12	316	1038
-	BP-3W	Beaverhill Lake	Lsd 5-21-95-12	344	1128
-	BP-4WA	Clearwater	Lsd 9-20-95-12	344	1128
-	HOME 4	McMurray	Lsd 3-28-94-9	324	1064
-	FINA 73-6	McMurray	Lsd 9-9-96-10	299	980
-	FINA 73-2	McMurray	Lsd 1-1-96-11	287	942
-	TENNECO 1	McMurray	Lsd 10-20-96-7	341	1120
-	SHELL OBS-7	Beaverhill Lake/Methy	Lsd 10-25-95-10	290	953
-	SHELL PW-4	McMurray	Lsd 10-25-95-10	291	955
-	SHELL PW-2	McMurray	Lsd 10-24-95-9	321	1054

GEOLOGICAL LEGEND FOR BULLETIN 38, APPENDIX 2

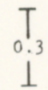


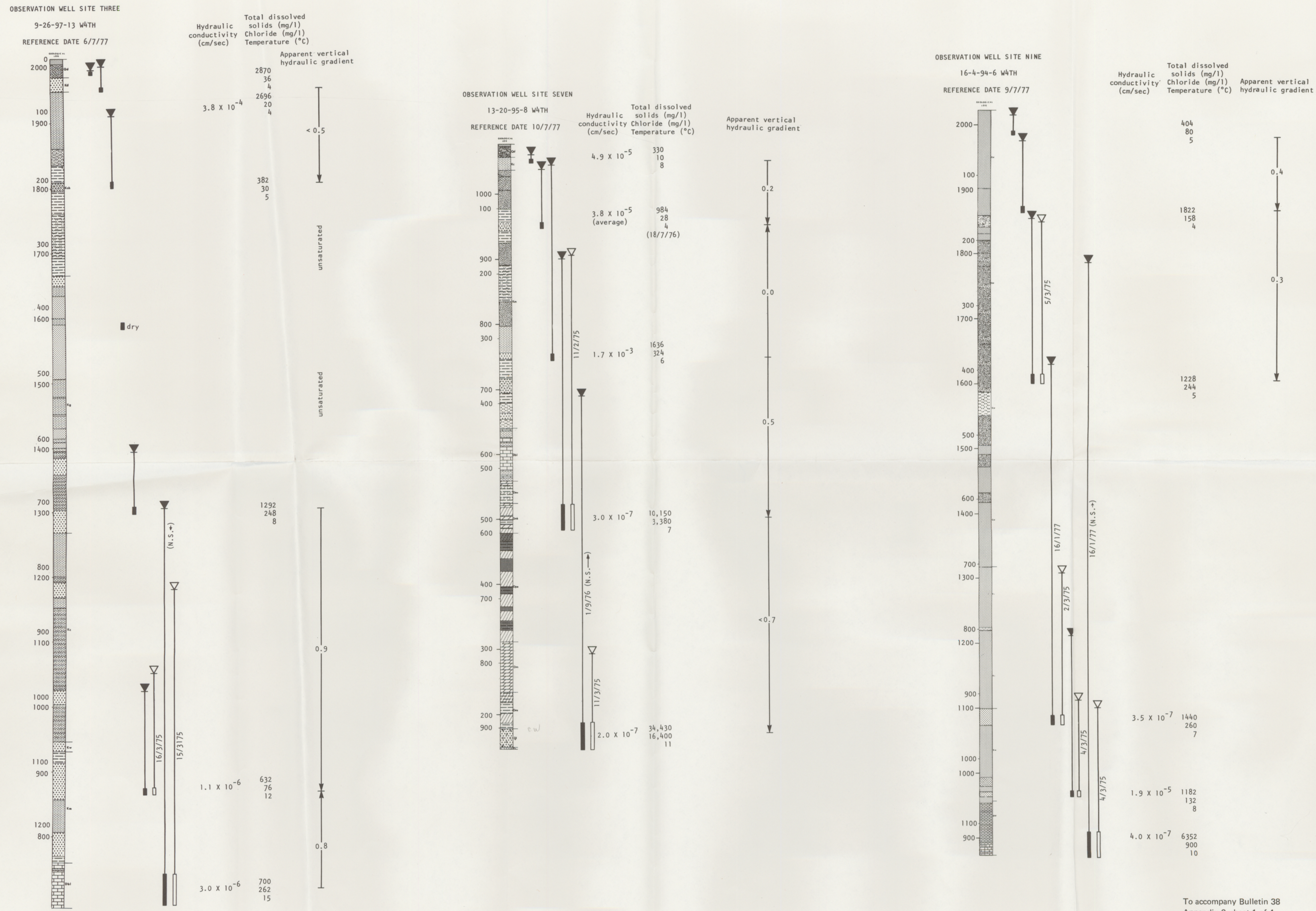
Symbol	Rock Unit
	till
	sand & gravel
	sand
	sandstone
	sandstone, arkosic
	silt
	siltstone
	siltstone & sandstone
	clay
	clay, sandy
	claystone, shale
	sandstone & shale
	oil sand
	limestone
	limestone, shaley
	dolomite
	dolomite, argillaceous
	rock salt
	gypsum & anhydrite
	coal
	igneous rock

Symbol	Stratigraphic Unit
Pleistocene and Recent	
Qd	Surface deposits
Cretaceous	
Ks	Smoky Group
Klb	La Biche Formation
Kd	Dunvegan Formation
Ksh	Shaftesbury Formation
Kpl	Pelican Formation
Kj	Joli Fou Formation
Kg	Grand Rapids Formation
Kc	Clearwater Formation
Kw	Wabiskaw Member
Km	McMurray Formation
Devonian	
Dwd	Woodbend Group
Dbl	Beaverhill Lake Formation
Dsw	Slave Point Formation & Fort Vermilion Formation & Watt Mountain Formation
Dmk	Muskeg Formation
Dpe	Prairie Evaporite Formation
Dm	Methy Formation (Keg River Formation equivalent)
Dmr	McLean River Formation (Chinchaga Formation equivalent)
Dl	La Loche Formation
Precambrian	
P€	Undivided

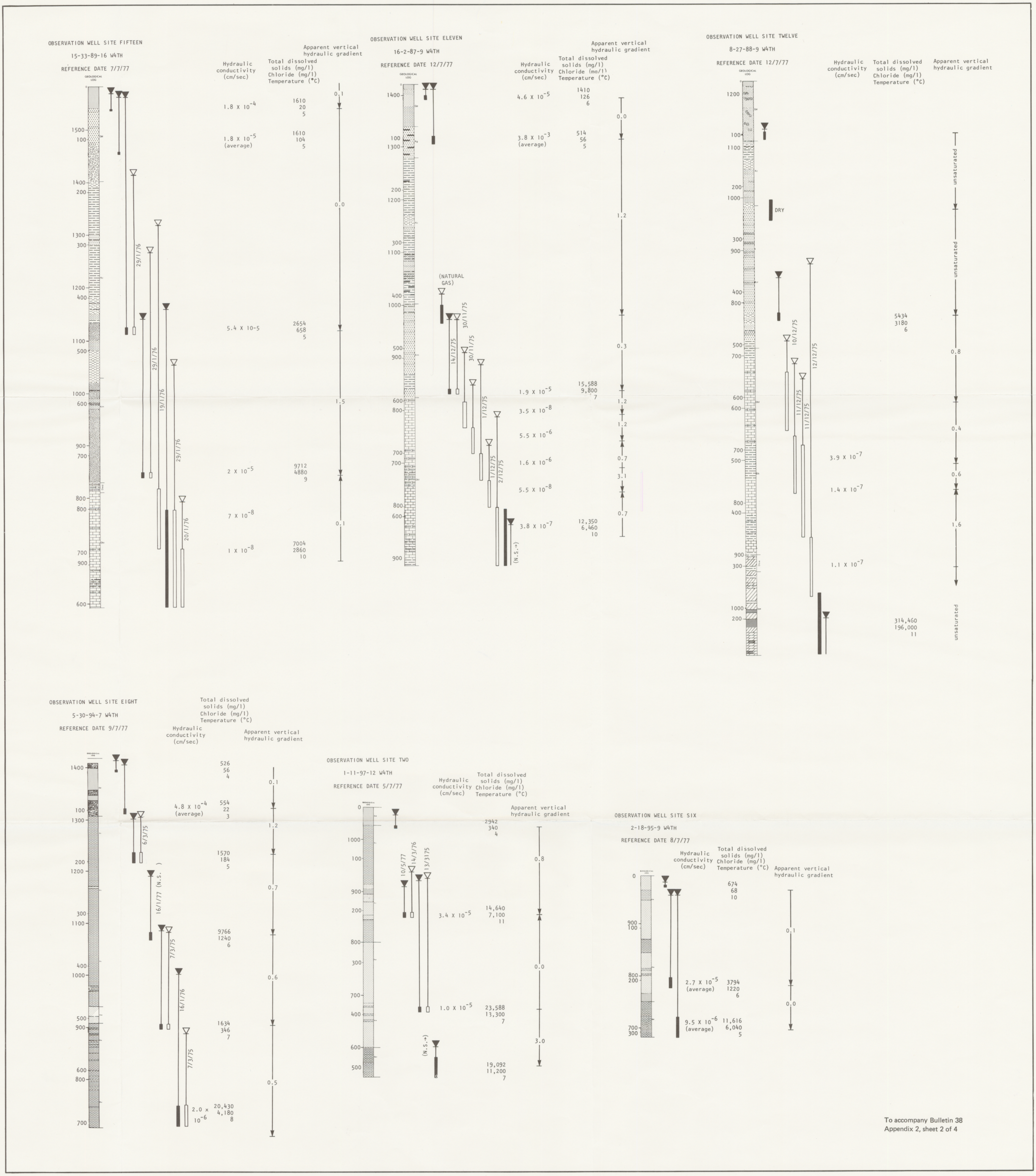
LEGEND

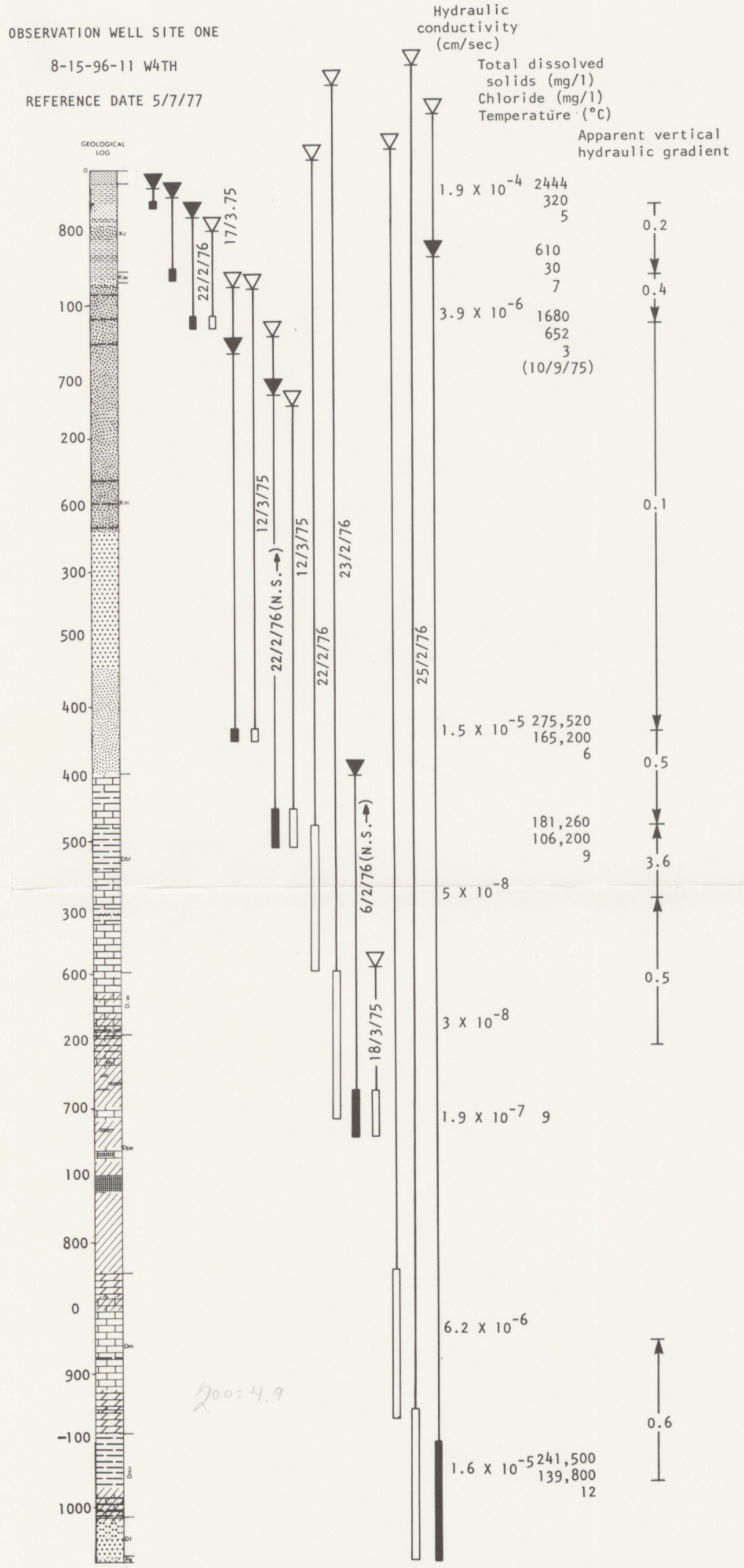
	Open or screened portion of well
	Open or screened portion of well during drill stem test
	Measured water level in well (point-water head)
	Measured water level in well recalculated to freshwater (freshwater head)
	Freshwater head calculated from extrapolated shut-in pressure from a drill stem test; date of test shown
Reference Date	All chemical information, water levels and temperatures were taken on this date unless otherwise noted
N.S. →	Water level indicated has not stabilized; arrow indicates direction of movement
17/7/76	Date of measurement of parameter; day/month/year
2000	Elevation - A.S.L. Datum
100	Depth - K.B. Datum
0.3	Apparent vertical hydraulic gradient and interval over which it is calculated. "Unsaturated" means a water table exists within the interval. Arrow indicates direction of gradient

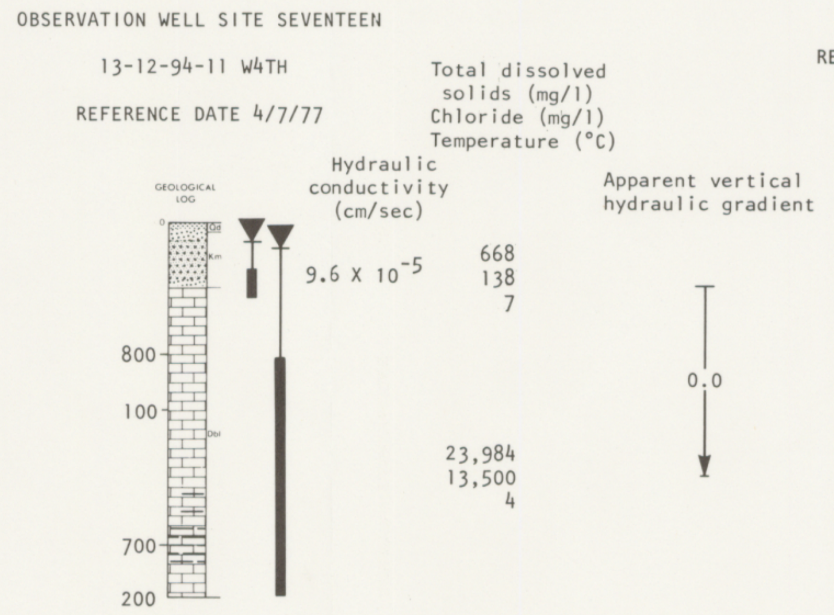


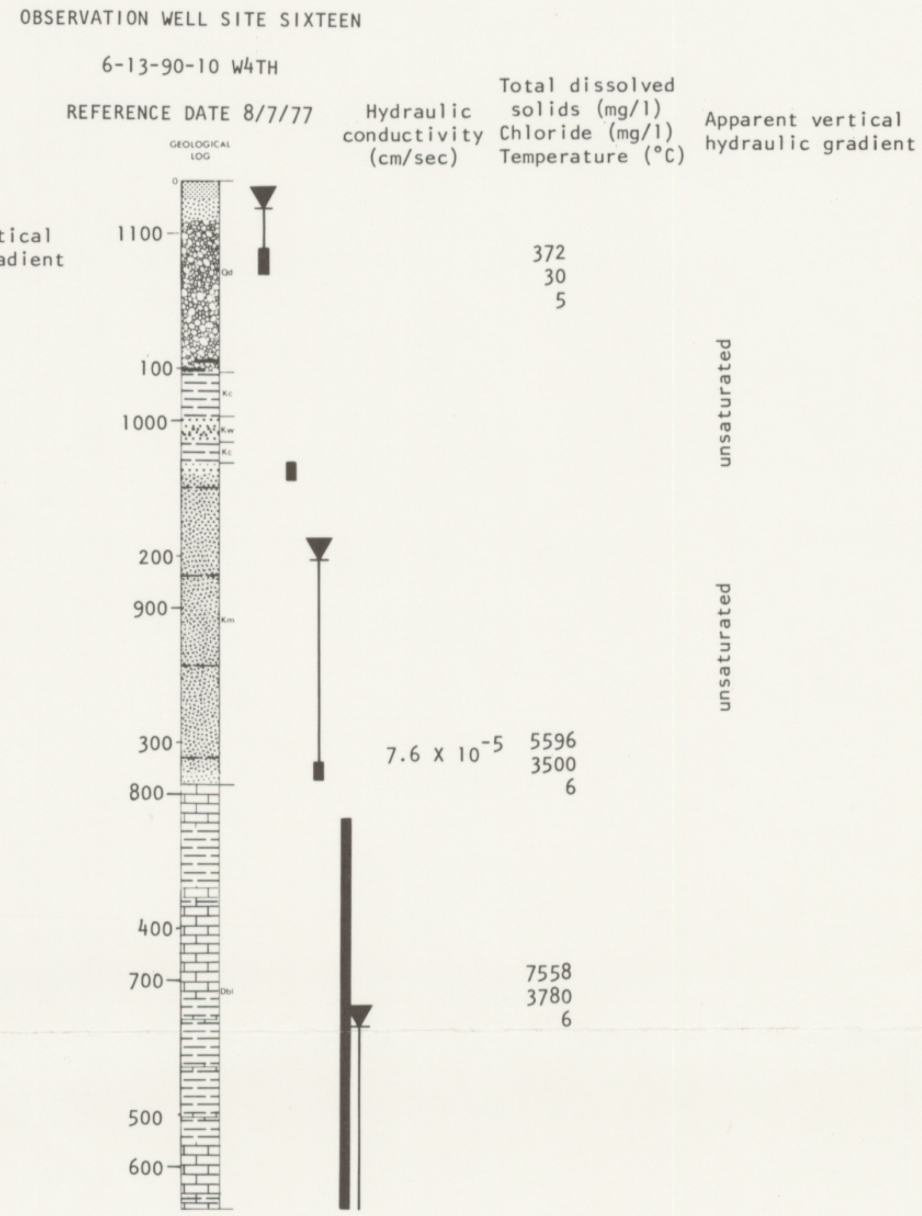


To accompany Bulletin 38
Appendix 2, sheet 1 of 4


OBSERVATION WELL SITE FIFTEEN
15-33-89-16 W4TH
REFERENCE DATE 7/7/77
Hydraulic conductivity (cm/sec)
Total dissolved solids (mg/l)
Chloride (mg/l)
Temperature (°C)
Apparent vertical hydraulic gradient
1.8 X 10^-4
1610 20 5
1.8 X 10^-5 (average)
1610 104 5
5.4 X 10-5
2654 658 5
2 X 10^-5
9712 4880 9
7 X 10^-8
1 X 10^-8
7004 2860 10
29/1/76
19/1/76
20/1/76
OBSERVATION WELL SITE ELEVEN
16-2-87-9 W4TH
REFERENCE DATE 12/7/77
4.6 X 10^-5
1410 126 6
3.8 X 10^-3 (average)
514 56 5
(NATURAL GAS)
30/11/75
14/12/75
1/12/75
2/12/75
1.9 X 10^-5
15,588 9,800 7
3.5 X 10^-8
5.5 X 10^-6
1.6 X 10^-6
5.5 X 10^-8
3.8 X 10^-7
12,350 6,460 10
(N.S.→)
OBSERVATION WELL SITE TWELVE
8-27-88-9 W4TH
REFERENCE DATE 12/7/77
DRY
unsaturated
10/12/75
11/12/75
12/12/75
5434 3180 6
3.9 X 10^-7
1.4 X 10^-7
1.1 X 10^-7
314,460 196,000 11
OBSERVATION WELL SITE EIGHT
5-30-94-7 W4TH
REFERENCE DATE 9/7/77
526 56 4
4.8 X 10^-4 (average)
554 22 3
1570 184 5
9766 1240 6
1634 346 7
6/3/75
16/1/77 (N.S. →)
7/3/75
16/1/76
2.0 X 10^-6
20,430 4,180 8
OBSERVATION WELL SITE TWO
1-11-97-12 W4TH
REFERENCE DATE 5/7/77
10/5/77
14/3/76
13/3/75
2942 340 4
3.4 X 10^-5
14,640 7,100 11
1.0 X 10^-5
23,588 13,300 7
(N.S.→)
19,092 11,200 7
OBSERVATION WELL SITE SIX
2-18-95-9 W4TH
REFERENCE DATE 8/7/77
674 68 10
2.7 X 10^-5 (average)
3794 1220 6
9.5 X 10^-6 (average)
11,616 6,040 5







To accompany Bulletin 38
Appendix 2, sheet 3 of 4

To accompany Bulletin 38
Appendix 2, sheet 4 of 4

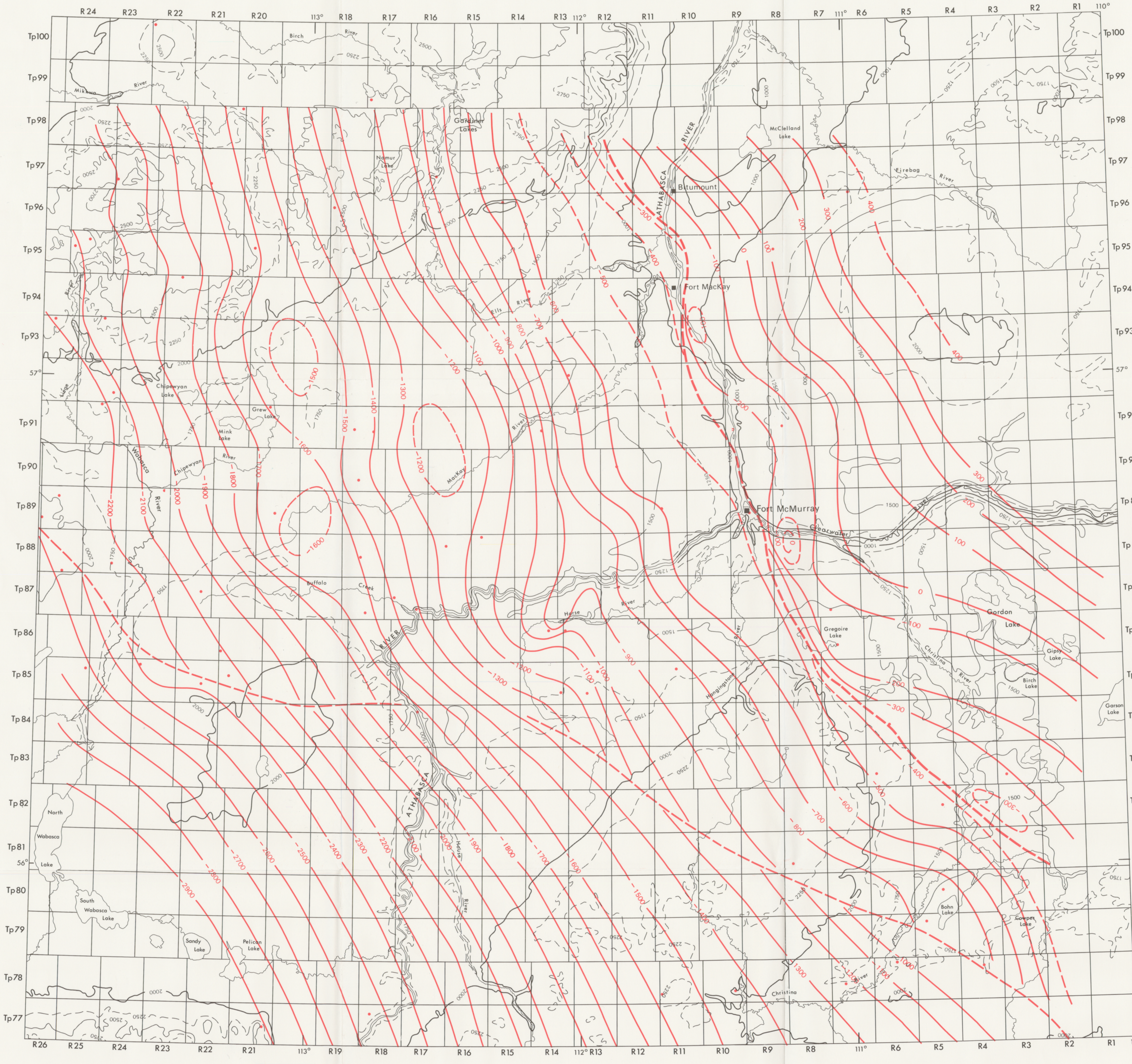


Figure 9. STRUCTURE CONTOURS ON THE PRECAMBRIAN SURFACE

SCALE 1:500,000

Miles 10 0 10 20 30 40 50 60 Miles

Kilometres 10 0 10 20 30 40 50 60 70 80 90 Kilometres

Legend

Data point ....

Structure contour on the surface of the Precambrian (contour interval, 100 ft):

defined ....

assumed ....

Fault, assumed ....

All elevations in feet above mean sea level

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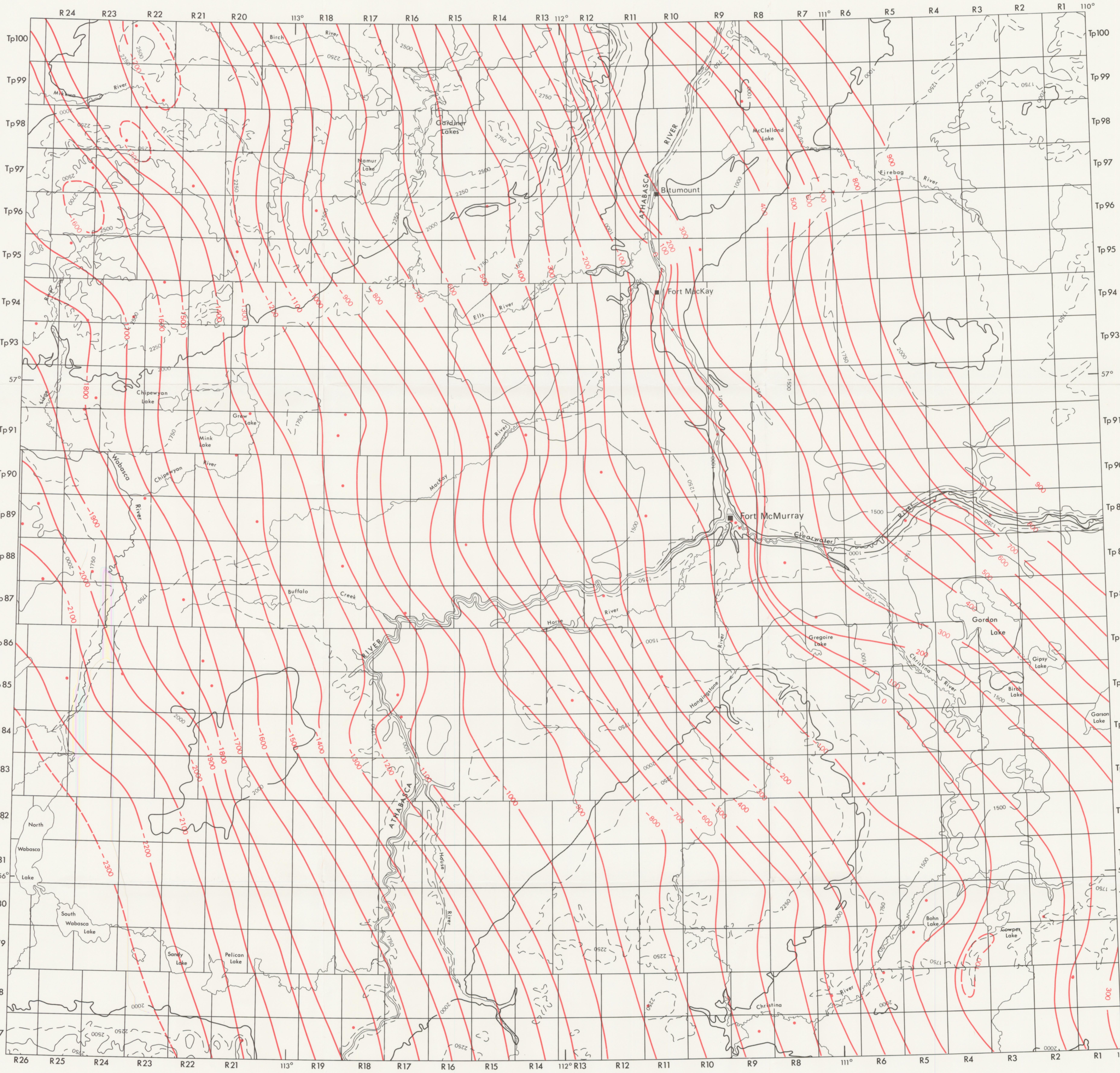

Figure 10. STRUCTURE CONTOURS ON THE METHY FORMATION

SCALE 1:500,000

Miles 10 0 10 20 30 40 50 60 Miles

Kilometres 10 0 10 20 30 40 50 60 70 80 90 Kilometres

Legend

Data point ....

Structure contour on the top of the Methy Formation (contour interval, 100 ft):

defined ....

assumed ....

depression ....

All elevations in feet above mean sea level

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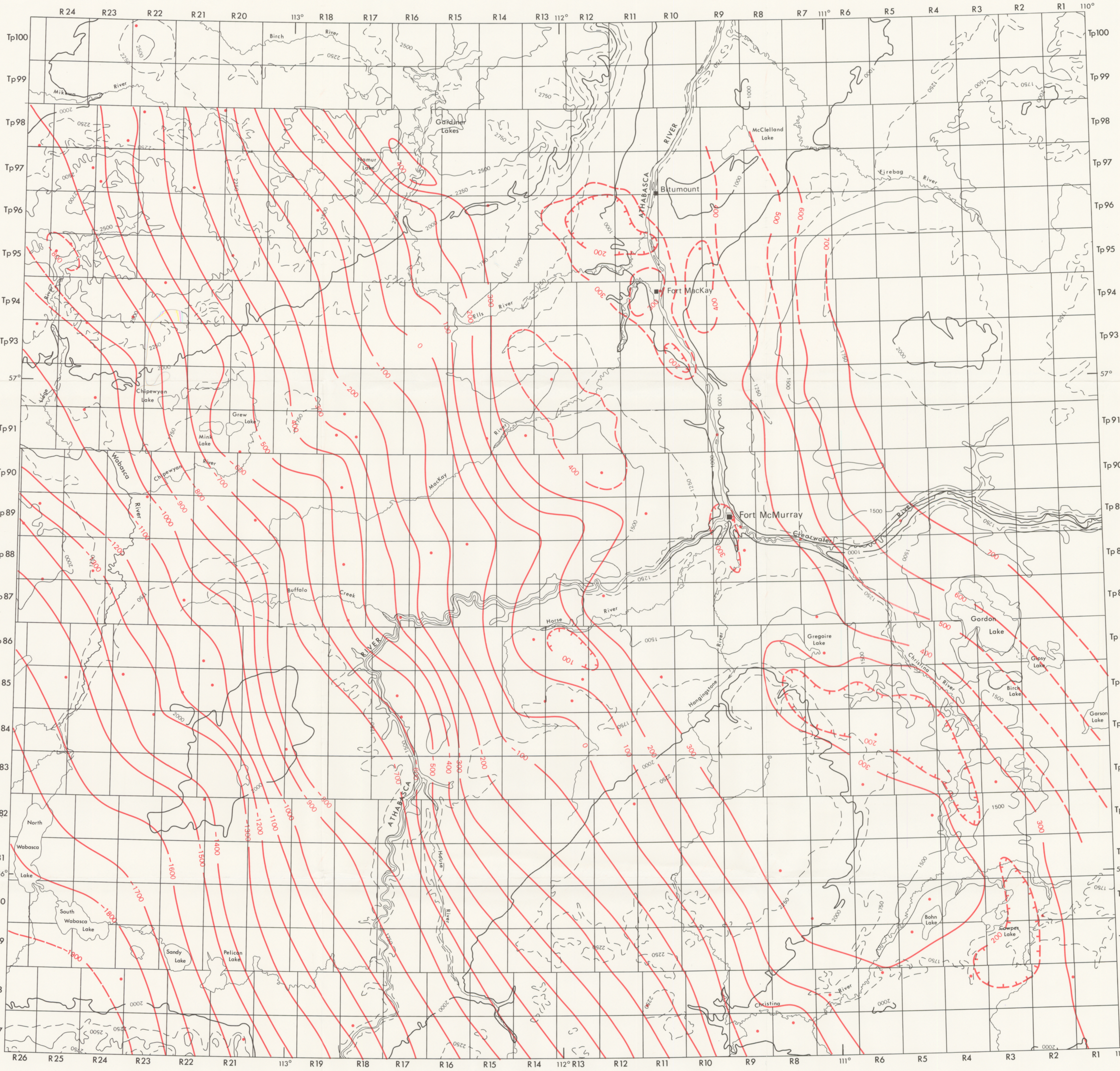

Figure 11. STRUCTURE CONTOURS ON THE PRAIRIE EVAPORITE FORMATION

SCALE 1:500,000

Miles 10 0 10 20 30 40 50 60 Miles

Kilometres 10 0 10 20 30 40 50 60 70 80 90 Kilometres

Legend

Data point ....

Structure contour on the top of the Prairie Evaporite Formation (contour interval, 100 ft):

defined ....

assumed ....

depression ....

All elevations in feet above mean sea level

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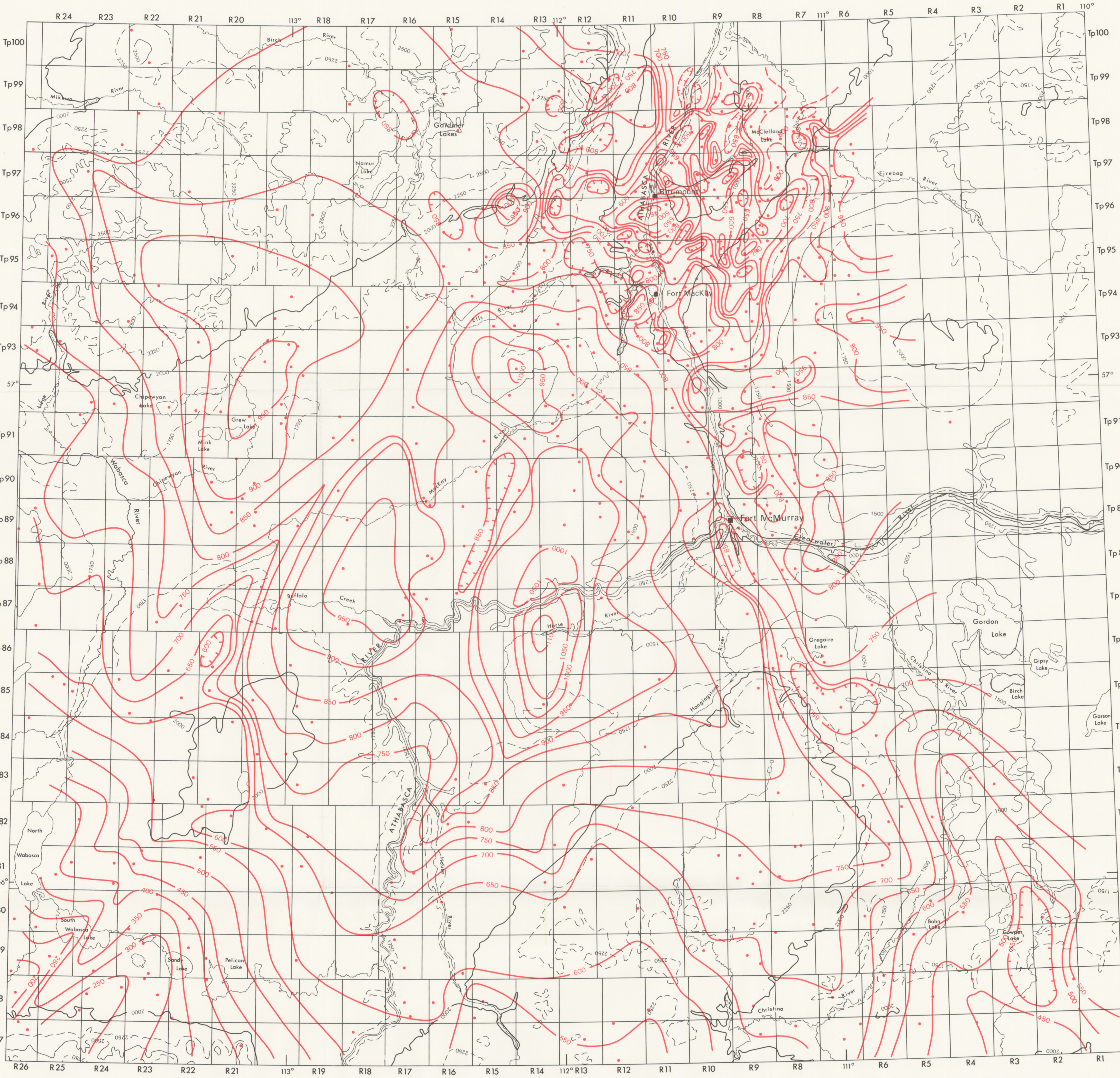

Figure 12. STRUCTURE CONTOURS ON THE PALEOZOIC SURFACE

SCALE 1:500,000

Miles 10 0 10 20 30 40 50 60 Miles

Kilometres 10 0 10 20 30 40 50 60 70 80 90 Kilometres

Legend

Data point ....

Structure contour on the surface of the Paleozoic (contour interval, 50 ft):

defined ....

assumed ....

depression ....

All elevations in feet above mean sea level

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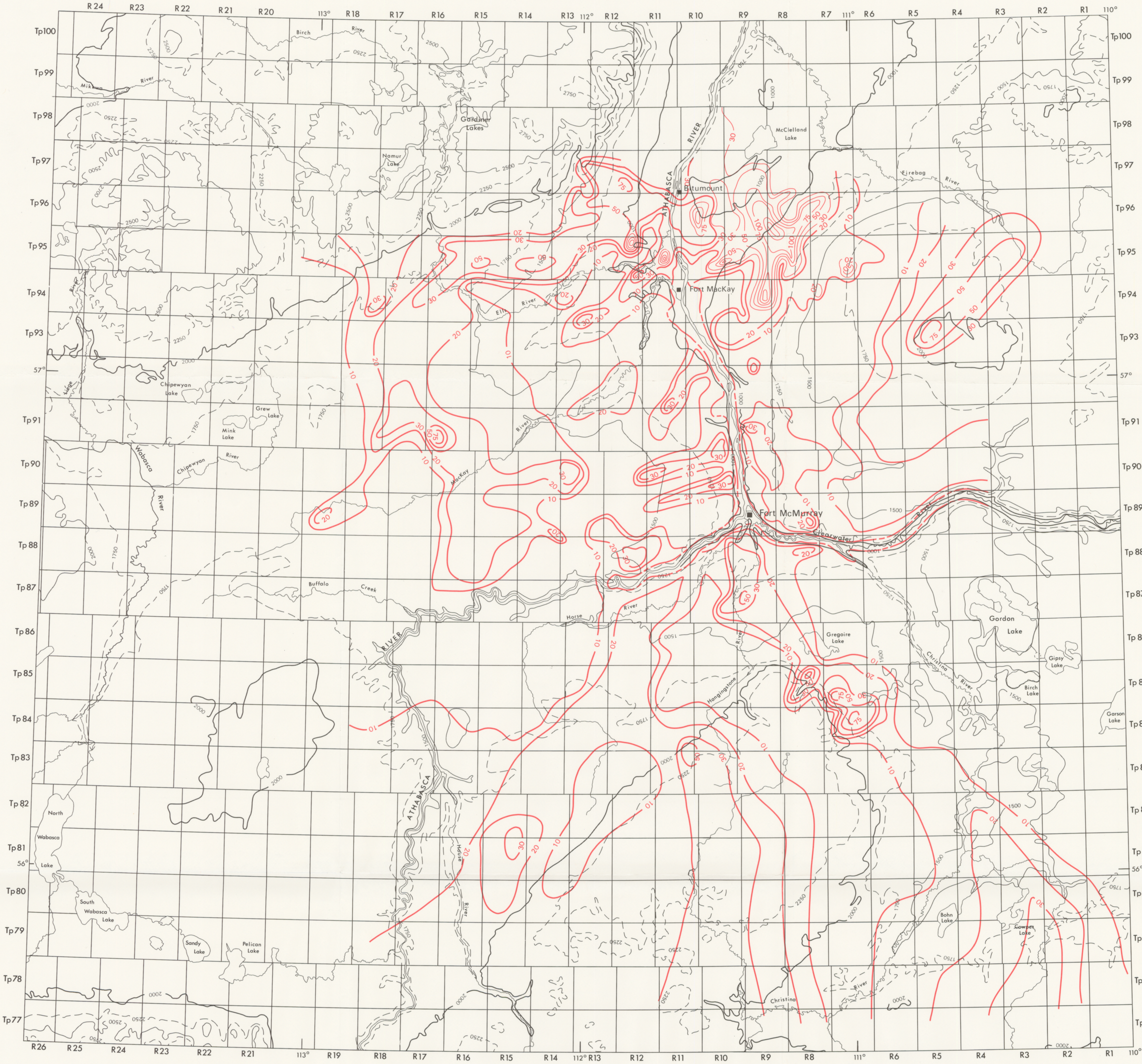

Figure 13. THICKNESS OF THE BASAL McMURRAY AQUIFER

SCALE 1:500,000

Miles 10 0 10 20 30 40 50 60 Miles

Kilometres 10 0 10 20 30 40 50 60 70 80 90 Kilometres

Legend

Isopach of basal McMurray aquifer (isopachs for 10, 20, 30, 50, 75, 100, 150 ft) ....

Geological boundary of McMurray aquifer ....

All elevations in feet above mean sea level

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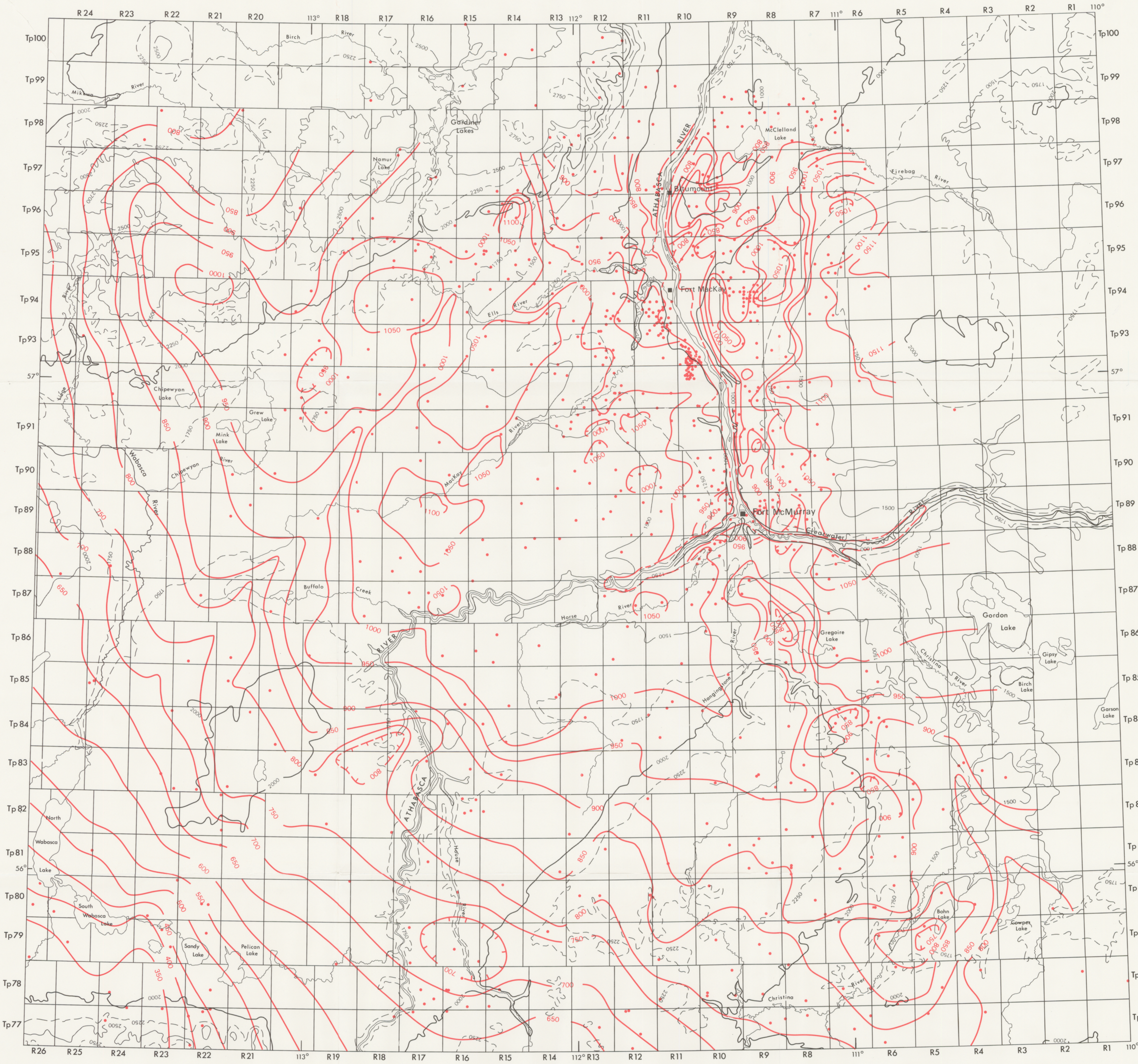

Figure 14. STRUCTURE CONTOURS ON THE McMURRAY FORMATION

SCALE 1:500,000

Miles 10 0 10 20 30 40 50 60 Miles

Kilometres 10 0 10 20 30 40 50 60 70 80 90 Kilometres

Legend

Data point ....

Structure contour on the top of the McMurray Formation (contour interval, 50 ft):

defined ....

assumed ....

depression ....

Geological boundary on McMurray Formation ....

All elevations in feet above mean sea level

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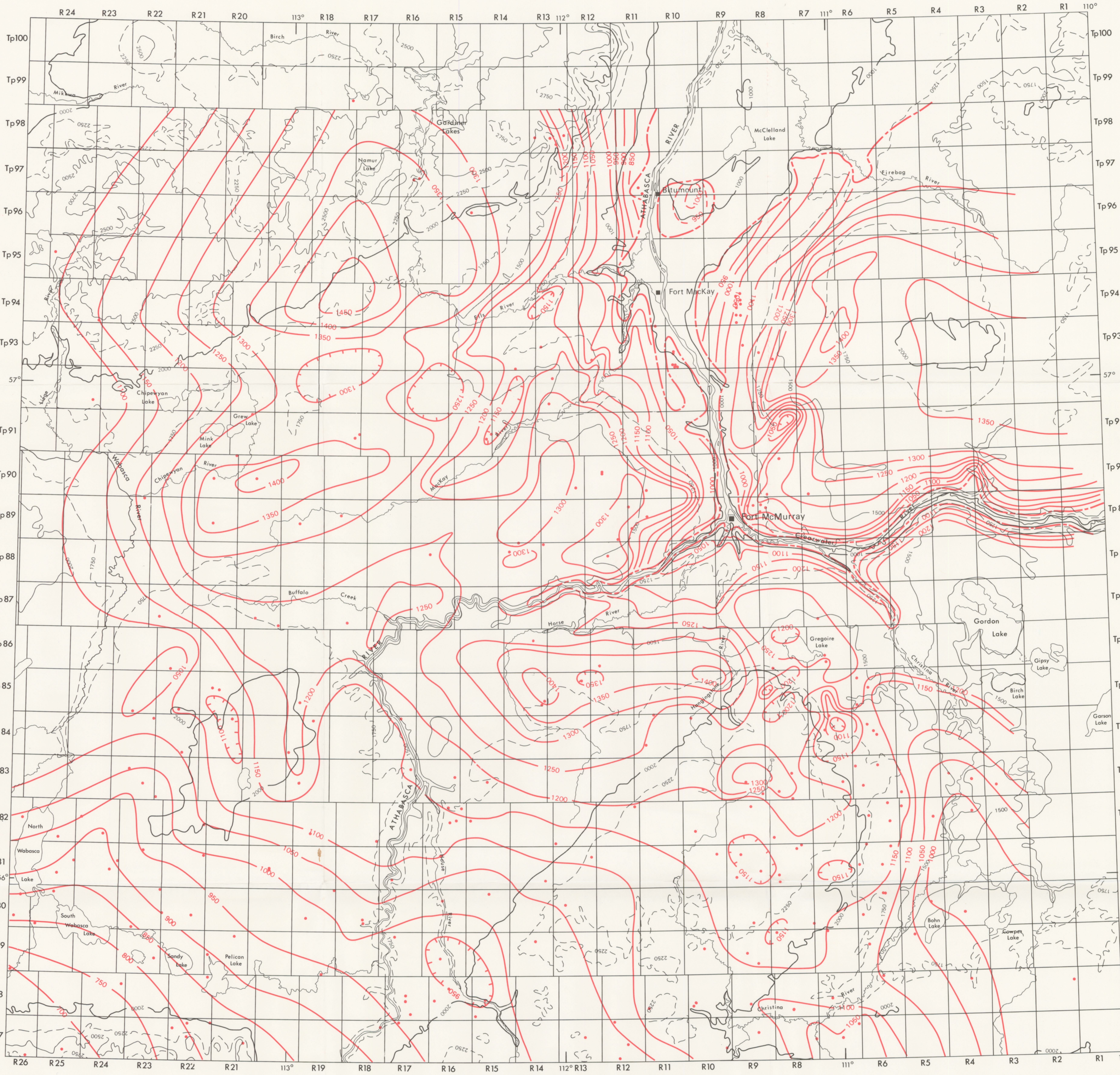

Figure 15. STRUCTURE CONTOURS ON THE CLEARWATER FORMATION

SCALE 1:500,000

Miles 10 0 10 20 30 40 50 60 Miles

Kilometres 10 0 10 20 30 40 50 60 70 80 90 Kilometres

Legend

Data point ....

Structure contour on the top of the Clearwater Formation (contour interval, 50 ft):

defined ....

assumed ....

depression ....

Geological boundary of Clearwater Formation ....

All elevations in feet above mean sea level

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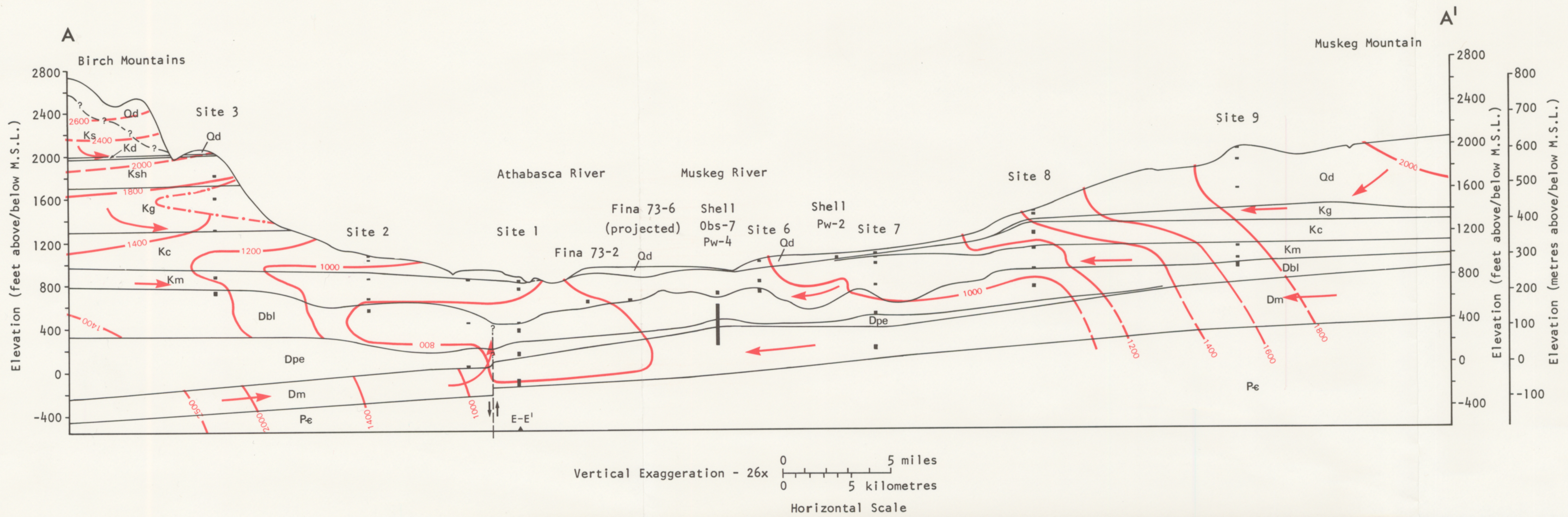

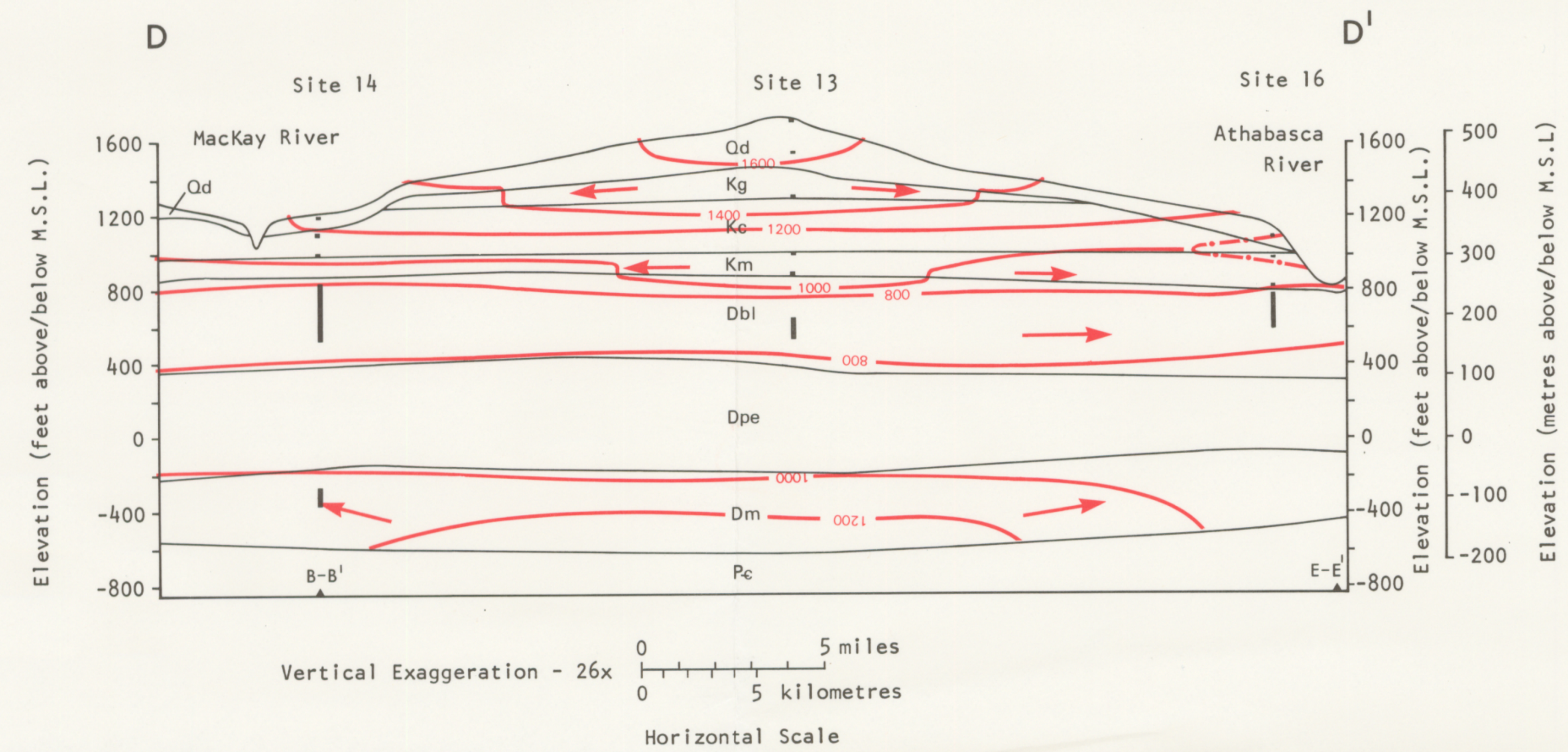

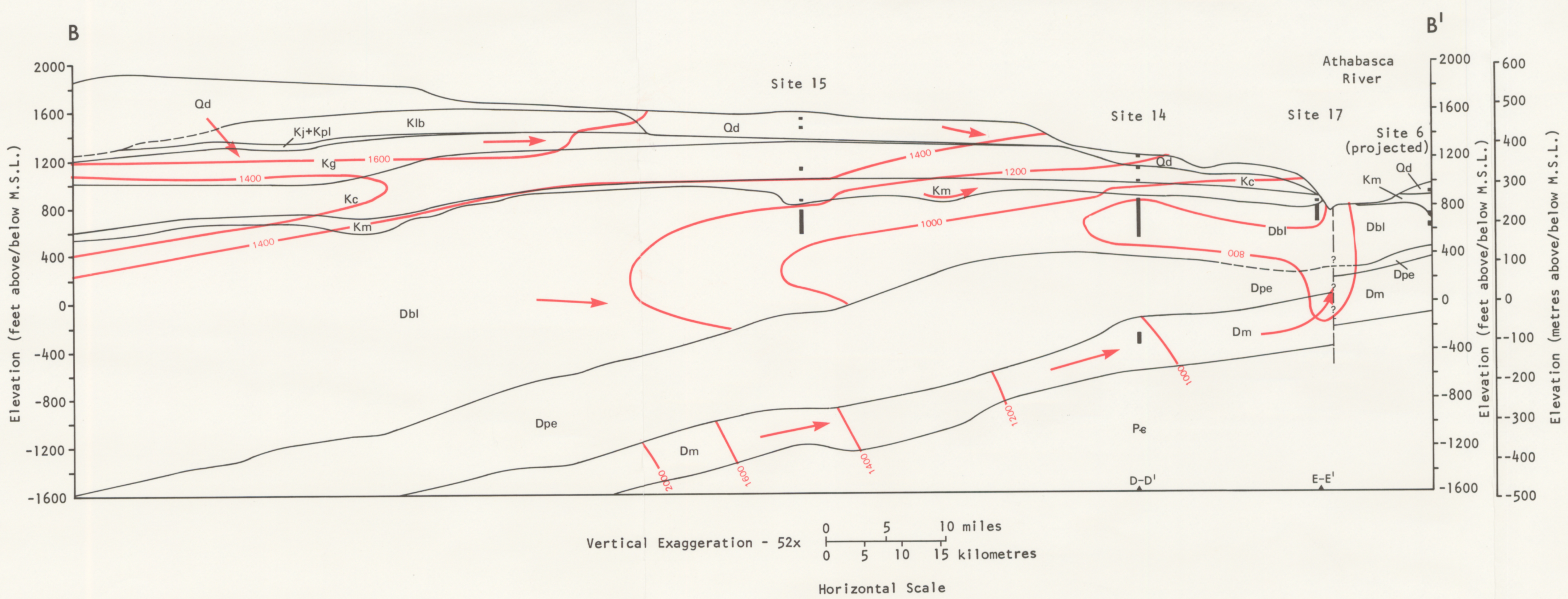

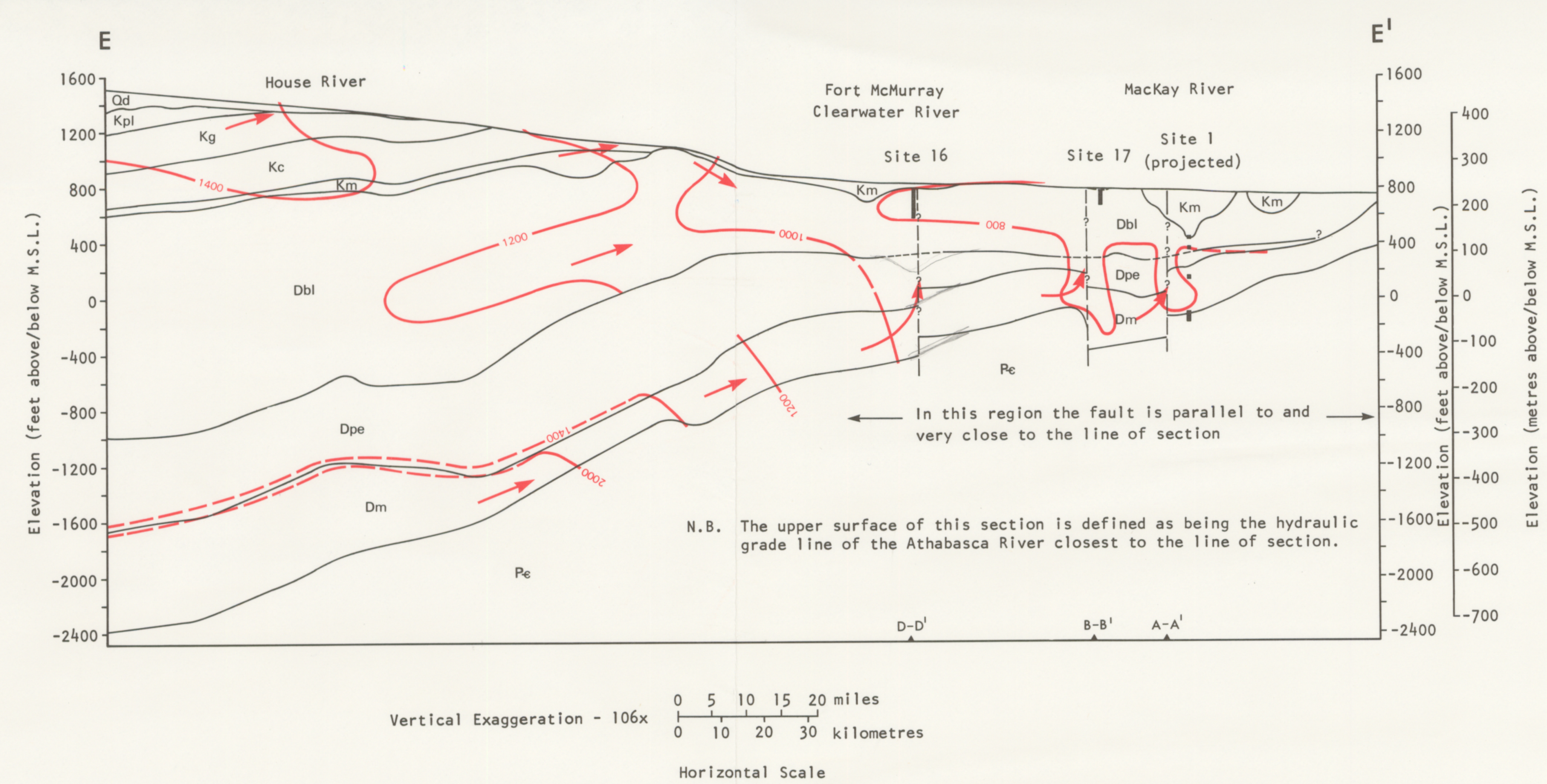

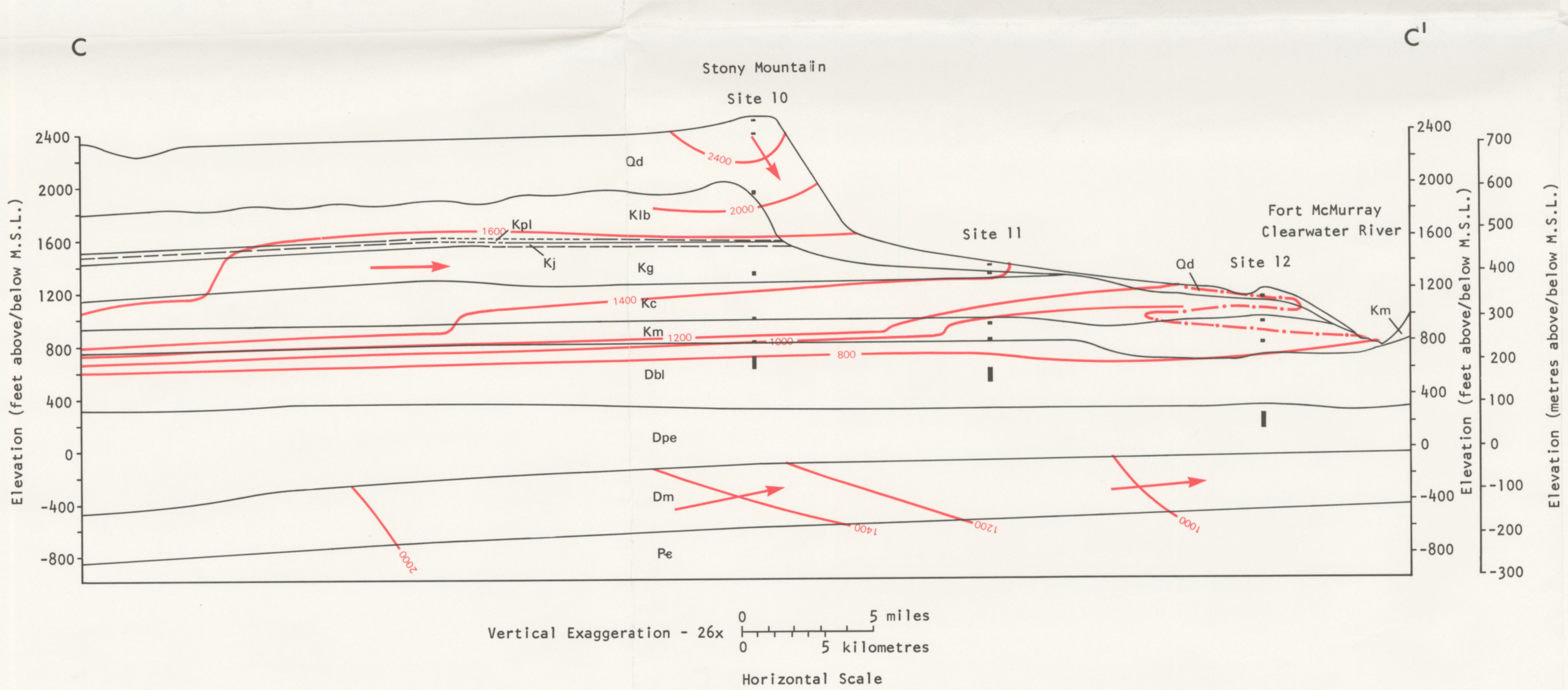

Figure 18. FRESHWATER HYDROLIC HEADS

LEGEND

— 1000 —	Freshwater hydraulic head in feet AMSL
→	Diagrammatic flow direction
▌	Open portion of observation well
-·-·-·	Water table
Qd	Glacial drift
Ks	Smoky Group
Klb	Labiche Formation
Kd	Dunvegan Formation
Ksh	Shaftesbury Formation
Kpl	Pelican Formation
Kj	Joli Fou Formation
Kg	Grand Rapids Formation
Kc	Clearwater Formation
Km	McMurray Formation
Dbl	Woodbend Group and Beaverhill Lake Formation
Dpe	Fort Vermilion, Watt Mountain, Muskeg, and Prairie Evaporite Formations
Dm	Methy, McLean River, and LaLoche Formations
	Precambrian

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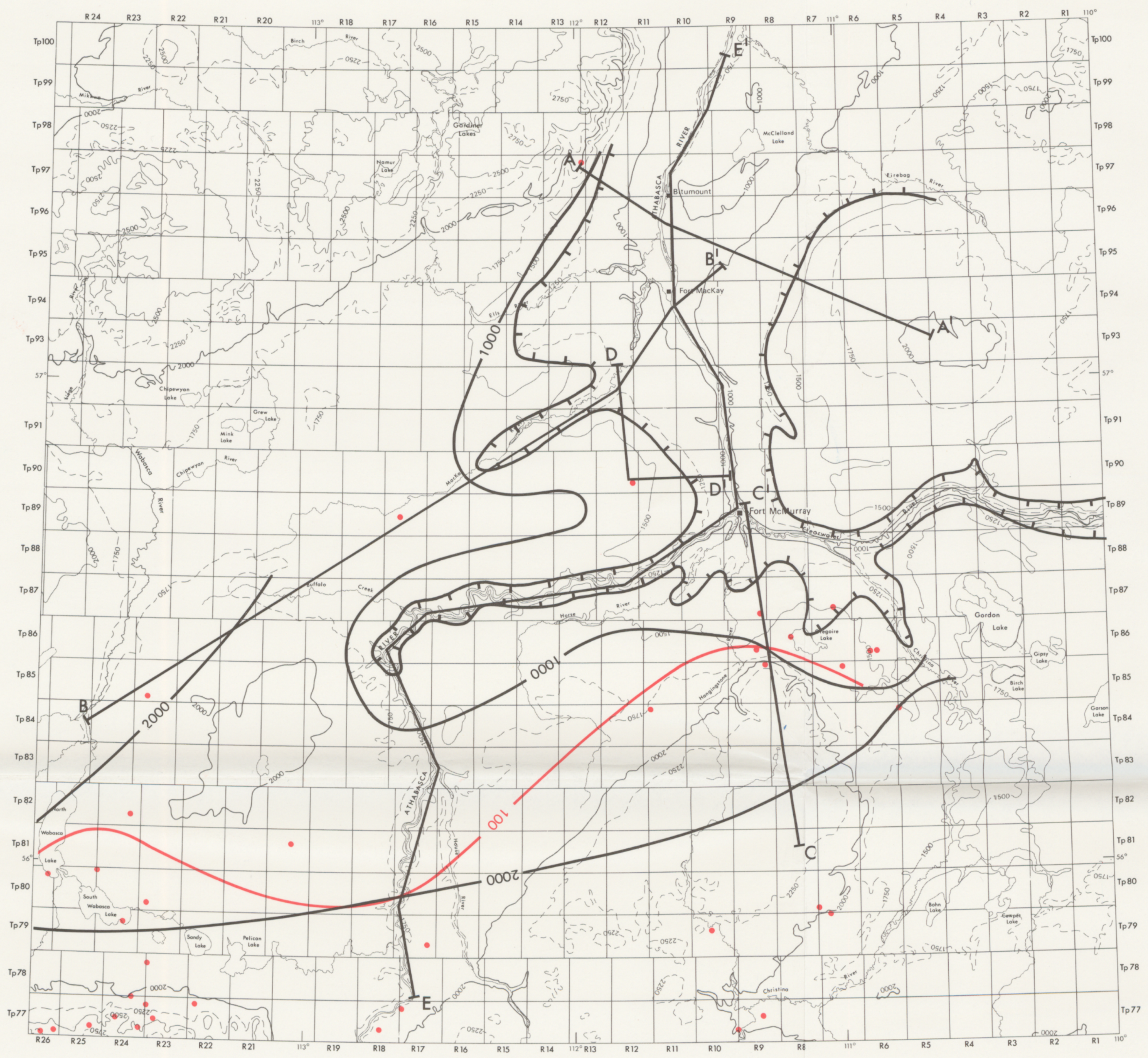
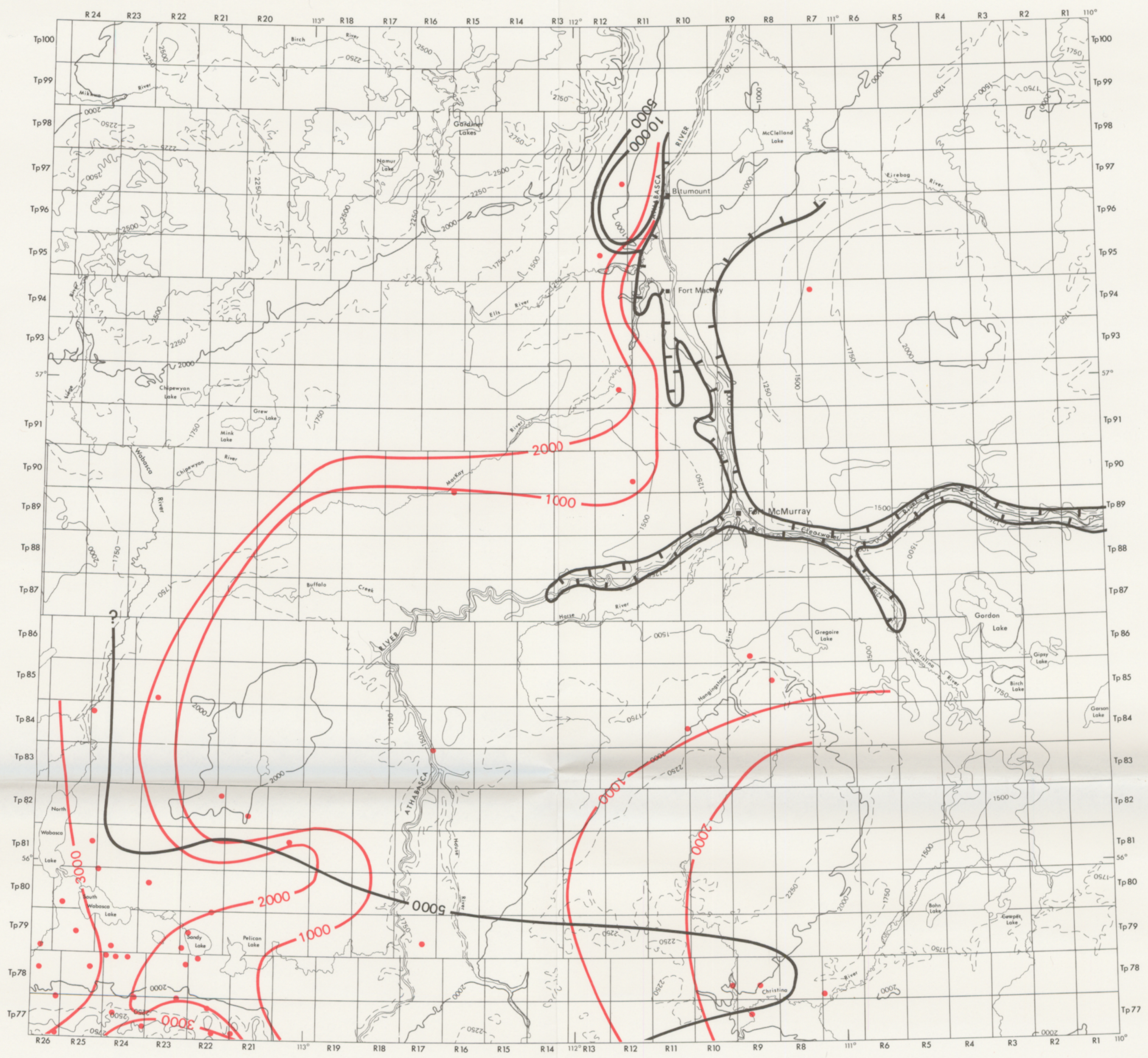
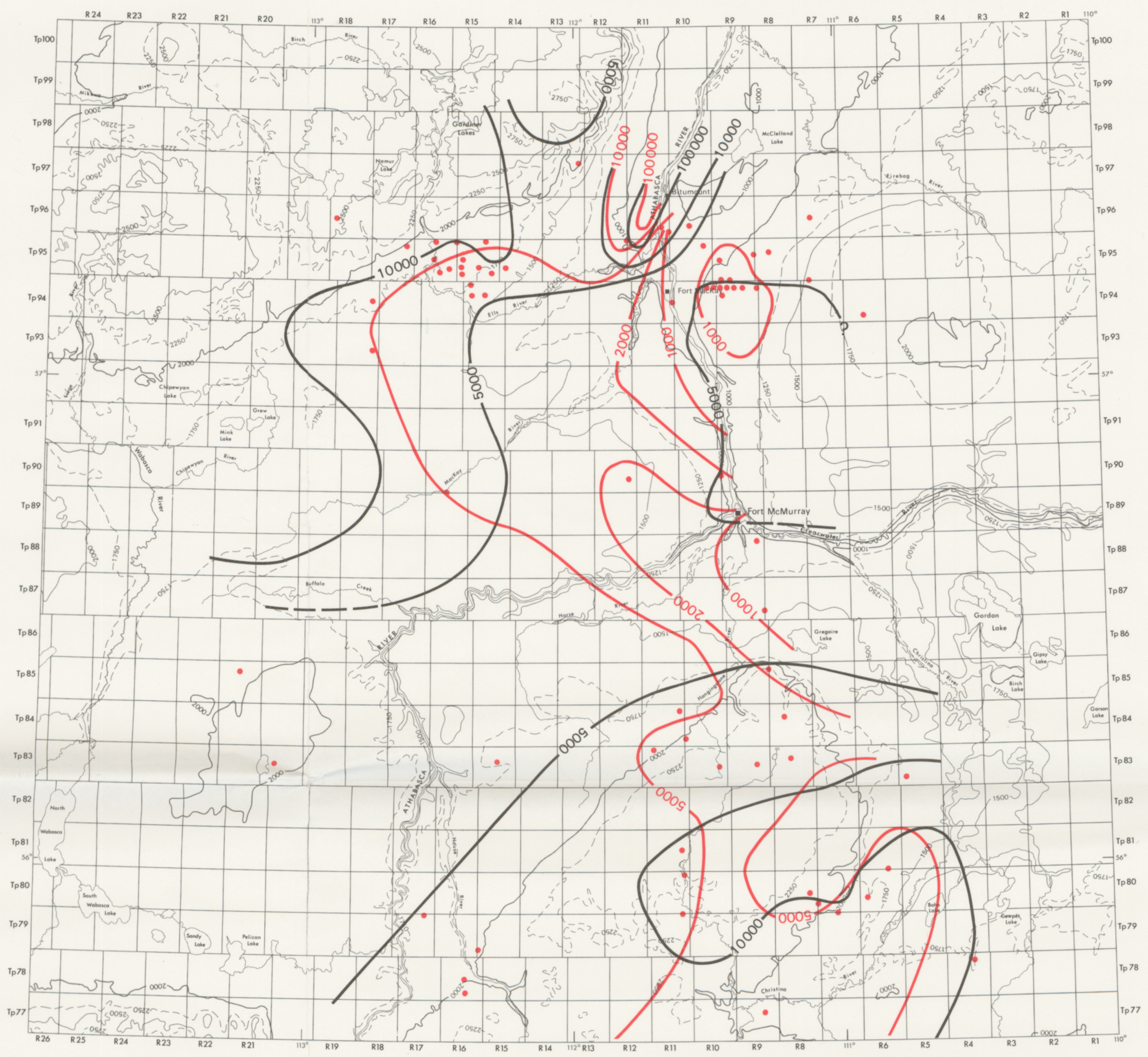


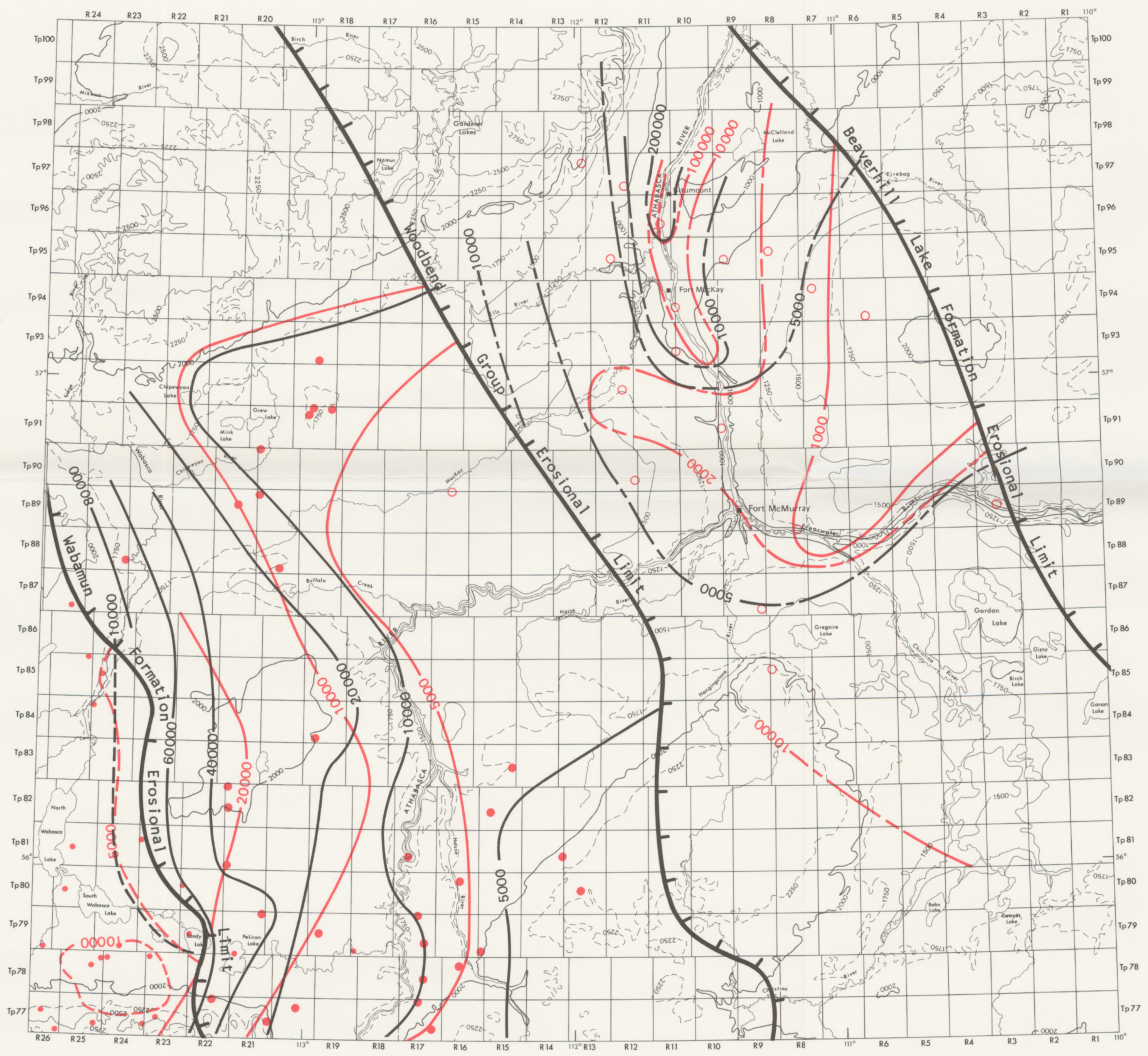
GRAND RAPIDS FORMATION



CLEARWATER FORMATION

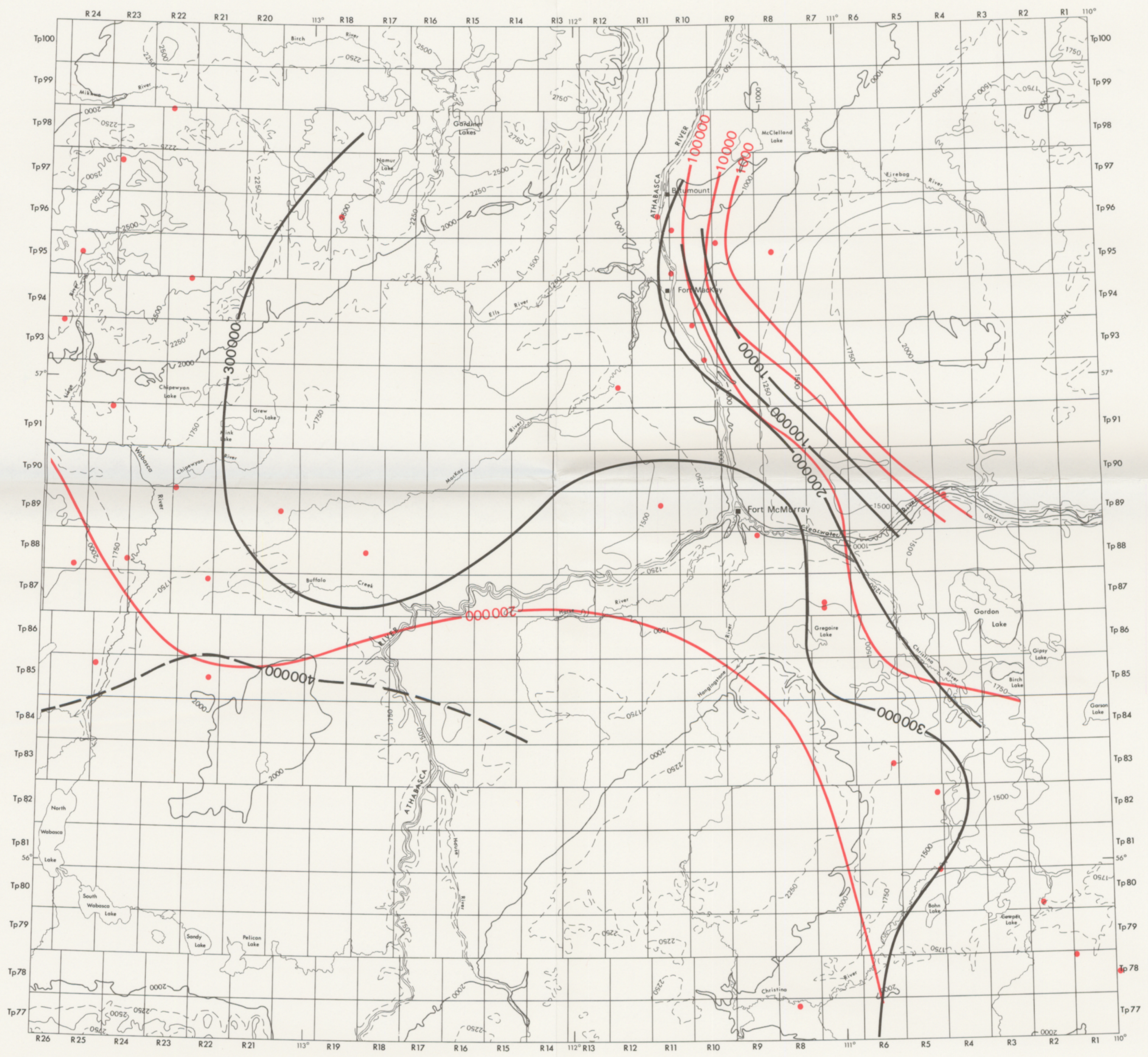


McMURRAY FORMATION



WABAMUN, WOODBEND AND BEAVERHILL LAKE FORMATION

Data point, Wabamun Formation .... •	Chloride concentration in mg/l in the Wabamun Formation	Total dissolved solids concentration in mg/l in the Wabamun Formation ....
Data point, Woodbend Group .... ●	Chloride concentration in mg/l in the Woodbend Group	Total dissolved solids concentration in mg/l in the Woodbend Group ....
Data point, Beaverhill Lake Formation .... ○	Chloride concentration in mg/l in the Beaverhill Lake Formation	Total dissolved solids concentration in mg/l in the Beaverhill Lake Formation ..



D-1 HYDROSTRATIGRAPHIC UNIT

Figure 23. TOTAL DISSOLVED SOLIDS AND CHLORIDE ION CONCENTRATIONS

SCALE

10 0 10 20 30 40 Kilometres

10 0 10 20 30 40 50 60 Miles

LEGEND

- Data point
- Erosional limit of Formation
- 5000 Total dissolved solids concentration in mg/l
- 2000 Chloride concentration in mg/l
- A A' Line of cross section

Location of formation contacts after:
Alberta Oil and Gas Conservation Board (1963)
Norris (1973)

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Figure 24. TOTAL DISSOLVED SOLIDS AND CHLORIDE ION CONCENTRATIONS

LEGEND

- 5000 — Total dissolved solids in Mg/L
- 1000 — Chloride in Mg/L
- ▌ Open portion of observation well
- Water table

Qd	Glacial drift
Ks	Smoky Group
Klb	Labiche Formation
Kd	Dunvegan Formation
Ksh	Shaftesbury Formation
Kpl	Pelican Formation
Kj	Joli Fou Formation
Kg	Grand Rapids Formation
Kc	Clearwater Formation
Km	McMurray Formation
Dbl	Woodbend Group and Beaverhill Lake Formation
Dpe	Fort Vermilion, Watt Mountain, Muskeg, and Prairie Evaporite Formations
Dm	Methy, McLean River, and LaLoche Formations
Pe	Precambrian

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