Geological Paper GP83-1

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## Part I: Current status and potential of subsurface disposal of fluid industrial wastes in Manitoba

By F. Simpson, H.R. McCabe and D. Barchyn

**Manitoba**
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**By F. Simpson,[1] H.R. McCabe[2] and D. Barchyn[3]**

**Winnipeg, 1987**



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## ABSTRACT

In recent years, subsurface injection has been adopted increasingly in Canada as a means of isolating liquid industrial wastes from the biosphere in order to minimize pollution hazard. Subsurface strata with adequate porosity and permeability, and potential for receiving fluid industrial wastes occupy two main areas in Manitoba: the Hudson Bay region in northeastern Manitoba, and the Williston Basin region in southwestern Manitoba.

Five main types of waste have been disposed of, stored, or treated in the subsurface strata of southwestern Manitoba:

1. *Brines* withdrawn during commercial production of crude oil (disposal: recycling of natural waste, very large volumes).
2. *Spent caustic waste* from the former Imperial Oil refinery in Winnipeg (disposal: highly toxic waste, but low volume).
3. *Spent cooling water* from air-conditioning systems in theatres and restaurants, and from cold-storage plants in central Winnipeg (disposal: recycling of natural formation fluid, moderate volume).
4. *Sewage* from the Virden and Portage la Prairie sewage treatment plants (treatment only: no emplacement of waste in subsurface, shallow to moderate depth).
5. *Low salinity brines* from backwash of water softening system, Manitoba Hydro, Dorsey converter station (disposal; moderate volumes, moderate depth, natural waste).

In addition to the above, several other types of waste are currently being considered for subsurface disposal. These are: salt water waste from fresh water supply plant using reverse osmosis process; nitrogenous waste from an estrogen-producing plant; and concentrated brine from a potash mill.

Emplacement of wastes underground in Manitoba has been carried out in areas of relatively good well control (oil wells, water wells, specific waste-management test holes). Consequently, many of the uncertainties inherent in underground waste management have been minimized, in particular those relating to reservoir geometry of the disposal formation, and, to a lesser extent, flow patterns of the formation fluids.

A regional review of the hydrogeology of southwestern Manitoba and Hudson Bay Lowland indicates that a number of hydrogeologic regions and zones can be defined, each with a distinctly different potential for subsurface disposal. Paleozoic strata of the Manitoba Lowland Region and the Hudson Bay Lowland, in general, are not suitable for subsurface disposal other than for natural or non-toxic wastes. The zones most suitable for subsurface disposal are limited to Paleozoic strata of the Southwestern Upland Region. The upper zone of the Paleozoic sequence, in particular the oil-bearing Mississippian, seems to offer the best disposal potential. However, local structural and stratigraphic anomalies occur even within the favourable areas. These features can seriously downgrade the potential of strata for subsurface disposal locally, so detailed evaluation and testing of all proposed disposal sites is essential.

Present Manitoba government regulations prohibit subsurface disposal of wastes without government approval, but specific regulations controlling subsurface disposal have not yet been formulated.

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# FOREWORD

Treatment and disposal of all types of domestic and industrial waste products has come to be one of the prime concerns of modern society, and the threat to the environment of this steadily accumulating volume of waste material is rapidly becoming one of the main concerns of all governments. Manitoba is fortunate that toxic industrial wastes are not yet generated in large amounts, so that an opportunity exists to address the problem before sometimes irreversible environmental degradation has occurred.

In 1982, as part of a long range program to address the problem of waste disposal, the Department of Environment and Workplace Safety and Health commenced a program to manage all hazardous waste generated in Manitoba. This program has included such components as public education, public input through the hearing process, assessment of the hazardous waste problem, development of legislation and regulations, and the assessment of available technology.

At the present time it is the intent of the Department of Environment and Workplace Safety and Health that all of Manitoba's hazardous waste will be handled, treated and disposed of by a newly created Crown corporation known as the Manitoba Hazardous Waste Management Corporation. Design of treatment and disposal systems is one of the initial projects to be undertaken by the new corporation, and a worldwide review of hazardous waste treatment and disposal systems has identified a number of possible technologies, one of which is subsurface deep well injection, the subject of this paper. One current example of utilization of subsurface disposal in an overall waste disposal strategy is that of the Alberta Special Waste Management Corporation which has incorporated injection technology as a component of their system. Non-hazardous waste water generated by a hazardous-waste treatment plant will be disposed of by deep well injection.

Currently, considerable injection of non-toxic fluid wastes into deep wells takes place in Manitoba, as outlined in this report, and further utilization of this means of disposal will undoubtedly be necessary, especially when major operations such as the planned potash mine come on stream. In all cases, however, destruction (or recycling) of waste material is preferable to any other type of disposal, and subsurface disposal is in fact a method of permanent storage of waste at a site remote from the surface environment. The problem, however, is that it is not possible to guarantee that the material injected into the subsurface at depth will never leak to the surface. This paper presents an evaluation of subsurface geological conditions throughout Manitoba and attempts to identify those areas where some potential exists for utilization of deep-well waste disposal. Of equal or greater importance is the delineation of areas where subsurface disposal should not be permitted because of unsuitable geological conditions.

Comprehensive programs for handling all types of hazardous waste will necessarily involve utilization of a wide range of technologies, and this present report provides the preliminary geological base required for evaluation of one of these potential technologies — deep-well subsurface disposal.

February 1987

N.B. Brandson
Director
Environmental Management Services

# 1.0 INTRODUCTION

### 1.1 General Statement

This paper is directed primarily to an evaluation of the potential for deep-well disposal of liquid toxic wastes in the subsurface sedimentary strata of Manitoba. However, disposal of non-toxic (but undesirable) waste at shallow depth is also a concern, and it is expected that initial subsurface disposal operations in Manitoba will be mainly of this type. Because of this, the scope of this paper has been broadened somewhat to include all types of subsurface liquid waste disposal as well as certain subsurface storage and processing operations that could potentially give rise to some type of subsurface pollution.

Deep-well disposal of fluid industrial wastes has become important in North America during the past twenty years, as a means of isolating noxious substances in geologic settings remote from the biosphere. Warner and Orcutt (1973) noted that prior to the year 1960 only 22 waste-injection systems had been initiated in the United States, whereas by June, 1973, some 278 disposal wells had been drilled in 24 states. Over a comparable time period, Canada has witnessed a proportionally greater increase in adoption of deep-well injection as a waste-disposal option: Simpson (1975a, 1976) noted the localization of Canadian subsurface-disposal facilities in (1) the northern Great Plains region in the west and (2) that part of the Great Lakes megalopolis located in southwestern Ontario in the east. Only 4 disposal systems had been initiated in Canada by 1960, but by mid-1975 that number had grown to 88 (Simpson, op. cit.).

Currently, in Manitoba, 5 main types of waste are disposed of or stored in the subsurface strata of the southern part of the province (Fig. 8):

(1) Since 1953, *brines* produced during commercial production of crude oil have been injected back into Mississippian oil reservoir strata at depths ranging from 612 to 997 m below surface. This reinjection not only has provided for waste disposal, but also has provided pressure maintenance in the oil reservoir strata, improving oil production and recovery.

(2) From 1969 to 1975, *spent caustic* solutions from the Imperial Oil Enterprises Limited oil refinery in Winnipeg were injected at low rates and low pressures into carbonate reservoir strata of the Lodgepole Formation (Mississippian) at depths of 634 to 652.9 m, in a reworked oil well of the Maples Field.

(3) *Spent cooling water* for air-conditioning systems in theatres and restaurants and from cold-storage plants in central Winnipeg is obtained from and then reinjected back into the Paleozoic carbonate aquifer, which has served these facilities since 1919.

(4) Commencing in 1986, the Manitoba Hydro Dorsey converter station, located at Sec. 8, Tp. 12, Rge. 1E, approximately 8 km northwest of Metropolitan Winnipeg, will dispose of approximately 7 million imperial gallons (6.8 million litres) of *waste brine* per year. The brine is produced as backwash from water softeners for the plant cooling system. Disposal is into the basal clastic division (Winnipeg Formation at a depth of 228 m [750 feet]).

(5) *Sewage* from the towns of Virden and Portage la Prairie is processed in large steel reactor vessels, up to 1.4 m in diameter, emplaced to depths of up to 150 m in clay, till and shale or limestone. These are purely subsurface treatment facilities; no processed or unprocessed waste should enter the subsurface environment.

### 1.2 Subsurface-Disposal: Objectives, Types of Disposal and Constraints

The prime objective of subsurface waste disposal is to emplace undesirable, frequently noxious substances into geologic settings remote from the biosphere, thus minimizing the hazard of surface pollution, particularly of potable water. Three main types of subsurface porosity form potentially suitable repositories:

(1) natural pore space occurring in subsurface strata. Where required, such natural porosity may be augmented by hydraulic fracturing or acidization of the rocks;
(2) artificial caverns and excavations, such as abandoned mine workings and salt caverns;
(3) artificial porosity and permeability created by hydraulic fracturing of impervious beds, usually shales.

Natural subsurface pore space is the type most frequently utilized by industrial operators in Canada, and is that most extensively discussed in the present account.

The main geological requirements necessary for implementation of any subsurface liquid-waste disposal programs, in natural porosity, in subsurface aquifers are:

(a) the injected wastes must be either contained at a specific location within the disposal strata, or confined to flow within a disposal aquifer that is isolated from the biosphere.
(b) the disposal strata must not be subjected to fracture deformation in response to the pressure of injection, as the wastes are emplaced. This does not apply in the case of artificially induced porosity.
(c) the injected fluid must be sufficiently compatible with the reservoir rock and natural reservoir fluid so that the reservoir will accept the waste fluid.

Simpson and Dennison (1975) discussed the need for rigorous, step-by-step analysis of any proposed system of regulations to control subsurface disposal. Stages in the life cycle of the subsurface-disposal decision system (rows in the matrix, presented as Figure 2A) should be analyzed with reference to the system-design process (columns of Figure 2A), shown in detail as Figure 2B.

Figure 3 shows a general model for design and evaluation of a system of regulations to control subsurface disposal of fluid wastes. This model has been adapted by Simpson and Dennison (op. cit.) from one described by Ellis and Keeney (1972), who considered a problem of air pollution and stressed the need to take into account undesirable "output" in policy formulation. The eventual escape of wastes from a subsurface disposal formation into the biosphere, with attendant adverse affects on any residents and the economy of the Province, would be the undesirable "output". It is therefore of utmost importance that careful consideration be given to the potential for creating such long-term pollution effects prior to undertaking any subsurface disposal program that might provide only short-term benefit. Pollution of groundwater supply can be close to irreversible, at least in the time frame relevant to local residents.

### 1.3 Legal Considerations

There is no legislation in Manitoba designed *specifically* for the regulation of subsurface-disposal procedures. Fluid injection of salt-water in both salt-water disposal and pressure-maintenance operations in oil fields is regulated by the Conservation Board of the Department of Energy and Mines, in accordance with the Mines Act of 1970 and subsequent amendments thereto. Disposal of refinery waste also has been administered under this Act. The Clean Environment Act of 1971, revised in 1972, was conceived for control of waste emission or discharge into air, water and "soil", and has general application to the modes of subsurface disposal discussed above; it is administered by the Environmental Management Services, Department of Environment and Workplace Safety and Health.

### 1.4 Procedure for Evaluation and Regulation of Subsurface Waste-Disposal Programs

Once a regulatory framework of some sort has been established, the next step is to carry out an evaluation of the available subsurface

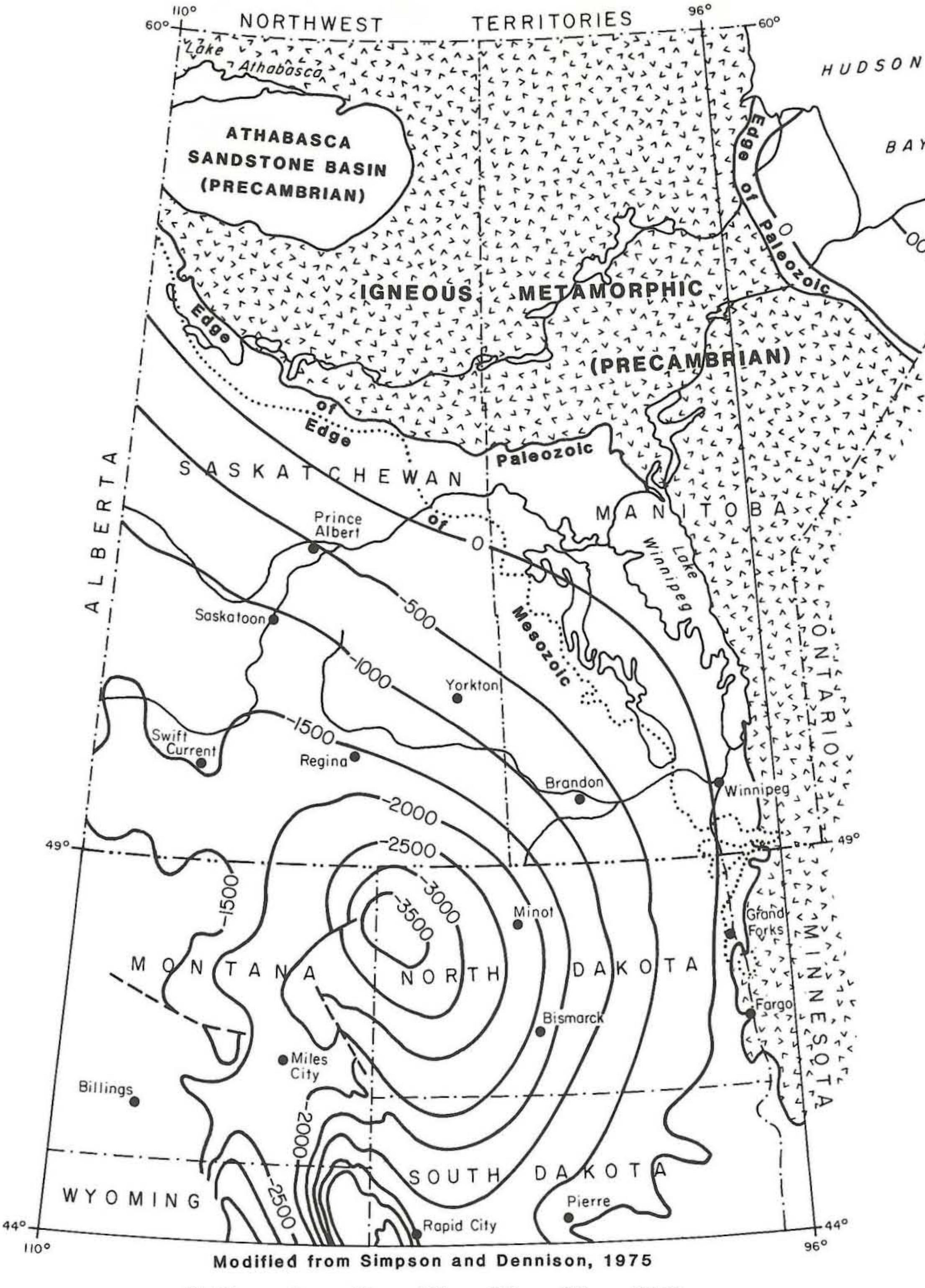



*Figure 1 Location map showing structure contours on Precambrian surface — Williston Basin area.*

| SYSTEM LIFE CYCLE | | | DESIGN PROCESS | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | COMPILATION OF INFORMATION | STRUCTURING OF PROBLEM | SYNTHESIS OF ALTERNATIVE SOLUTION | ANALYSIS + TESTS | EVALUATION | DECISION | OPTIMIZATION | COMMUNICATION + IMPLEMENTATION |
| SYSTEM LIFE CYCLE | PLANNING | CONCEPT FORMULATION | | | | | | | | |
| | | SYSTEM DEFINITION | | | | | | | | |
| | ACQUISITION | WASTE REDUCTION | | | | | | | | |
| | | DISPOSAL SITE | | | | | | | | |
| | | DISPOSAL FORMATION | | | | | | | | |
| | | DISPOSAL WELL | | | | | | | | |
| | | MONITORING DEVICE | | | | | | | | |
| | USE | OPERATION AND MAINTENANCE | | | | | | | | |
| | | ABANDONMENT + CONTINUED MONITORING | | | | | | | | |

*Figure 2A Life cycle/design process matrix for the subsurface disposal decision system.*

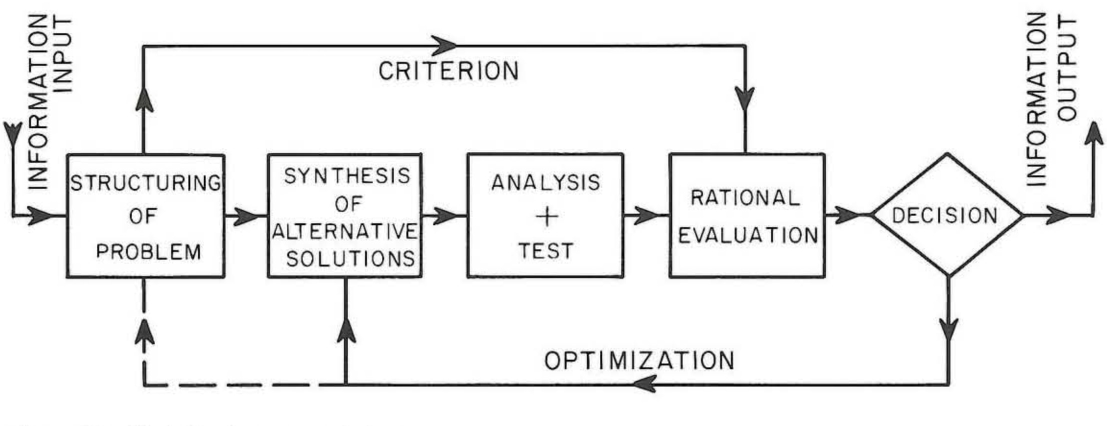



*Figure 2B Model for the system-design process.*

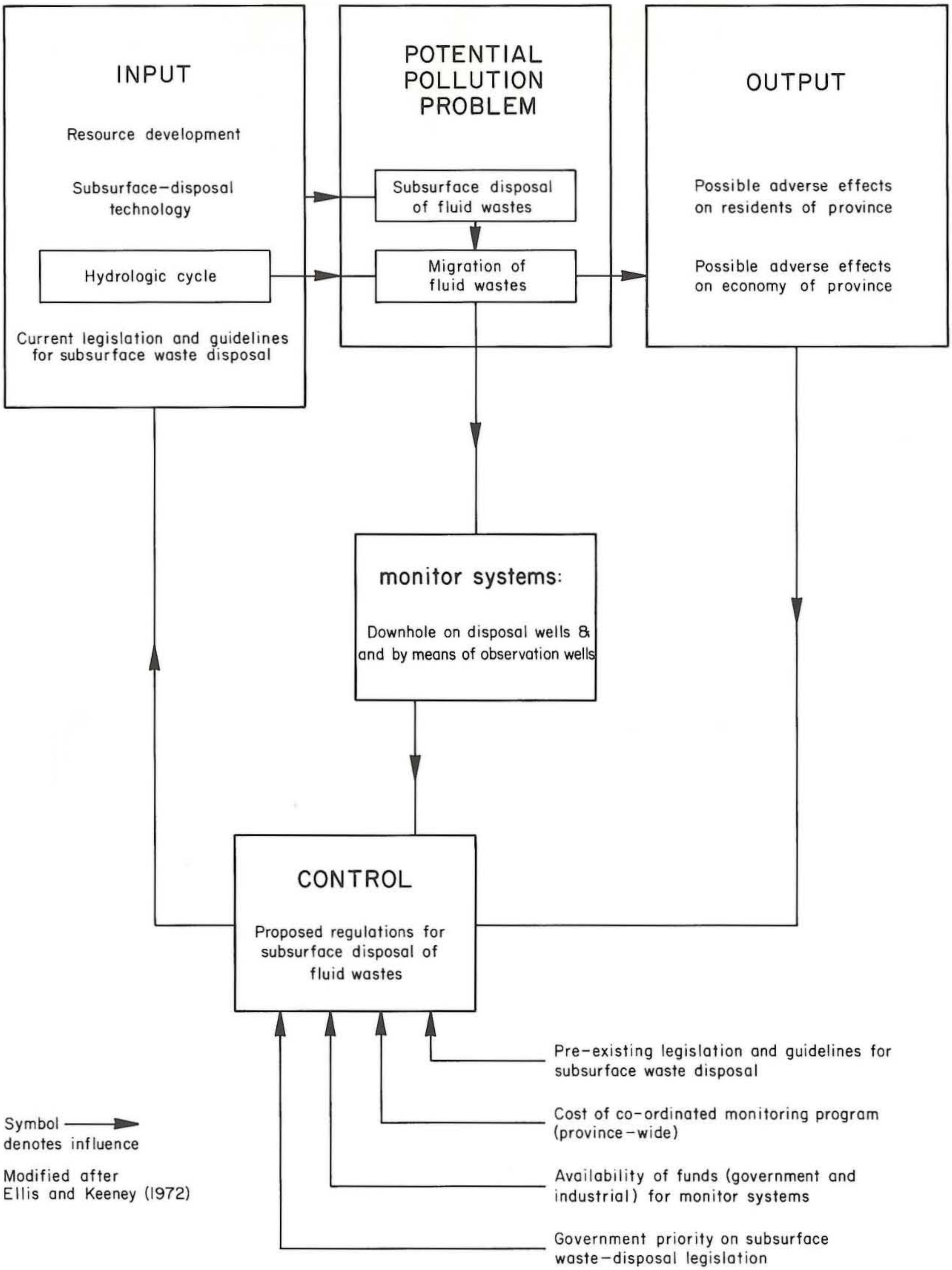



*Figure 3 General model for evaluation of regulations controlling subsurface disposal of fluid wastes.*

## TABLE I
### STEPS IN EVALUATION OF A PROPOSED SUBSURFACE-DISPOSAL PROGRAM[1]

| Process | Factors |
|---|---|
| 1. Regional evaluation of disposal potential | Thickness of sedimentary section, faulting, seismicity, regional hydrodynamics. |
| 2. Area and zone evaluation | Reservoir thickness, porosity, permeability, extent (capacity); detailed hydrodynamics; alternative resource use. |
| 3. Waste evaluation | Natural, foreign or radioactive; quantity; toxicity; compatibility with disposal zone; required treatment. |
| 4. Evaluation of alternative disposal methods | Economics; utilization of subsurface space for disposal is irreversible — use alternative disposal method if possible. |
| 5. Approval for site testing and site specific requirements | As No. 2, designation of detailed reservoir parameters required for specific waste type and volume; drilling of test hole to disposal zone. |
| 6. Approval for disposal project and designation of disposal parameters | Reservoir parameters meet specified requirements. Designate maximum waste injection pressure, maximum input rate, total volume, preliminary waste treatment, preliminary reservoir treatment, monitoring requirements. |
| 7. Stipulation of well abandonment program | On completion of disposal program or if required because of indicated containment failure. |

[1] Modified from van Everdingen and Freeze (1971).

disposal potential. Van Everdingen and Freeze (1971) present a detailed discussion of all geotechnical factors to be considered in evaluation of any proposed subsurface liquid waste disposal program; the indicated steps are summarized in Table I. They recommend that:

> "the first task of a regulatory agency would be to designate "potential", "limited" and "closed" disposal regions. ... Subsequently, potential disposal formations in the regions of the first two types would have to be subdivided into "favourable", "restricted" or "closed" zones."

Examination of the regional evaluation factors in Table I shows that the Phanerozoic areas of Manitoba comprise "potential" disposal zones. This report attempts to designate, at least in a preliminary way, the areal extent of "favourable", "restricted" and "closed" zones, particularly with respect to the southwestern, Phanerozoic region of the Province.

### 1.5 Measures of Subsurface-Disposal Effectiveness

The effectiveness and safety of a subsurface-disposal program can be ascertained only through careful monitoring of operations, based on a continuous record of all responses to waste disposal. The following monitoring operations should form the minimum monitoring scheme at any deep-well toxic waste disposal operation:

(1) the possibility of leakage of the disposal well and/or anomalous movement (or lack of movement) of wastes in the disposal formation should be checked by continuous observation of injection rate, injection pressure and annular pressure. All values must be maintained within prescribed limits.

(2) near-surface aquifers should be checked for contamination by means of shallow observation wells, preferably drilled to the deepest fresh-water aquifer.

(3) the rate of movement of the plume of injected wastes within the disposal strata should be monitored by means of observation wells drilled to the disposal zone.

### 1.6 Scope of Study

The present study does not attempt to cover in detail all aspects of subsurface disposal. For more detailed discussions of disposal regulations, injection well design, reservoir hydrodynamics during waste disposal, waste compatibility, etc., the reader is referred to McLean (1968) and van Everdingen and Freeze (1971). Simpson and Dennison (1975) present a comprehensive review of subsurface waste disposal for Saskatchewan, and much of this information is directly applicable to Manitoba.

The present account reviews the current status of subsurface waste disposal in Manitoba, with special emphasis on the emplacement of fluid industrial wastes into confined aquifers by means of injection down deep wells. The potential of the area to support additional waste-injection systems without deterioration of environmental quality is discussed in detail with reference to the general structural, stratigraphic and hydrogeologic setting of the area, and the experience of subsurface waste disposal in adjacent areas. An attempt is made to define and evaluate the different hydrogeologic regions and zones of the Province as to general potential for subsurface waste disposal. A detailed case history of deep-well injection of refinery wastes at the Maples oil field, previously outlined by Simpson (1978a), will be presented in Simpson and McCabe (in preparation: Part II of this report).

Initial compilation of this report was done by F. Simpson, utilizing all available published stratigraphic and hydrogeologic information, as well as data obtained from a previous study of the subsurface-disposal potential of southern Saskatchewan (Simpson and Dennison, 1975). Additional structural and stratigraphic data for Manitoba were supplied by H.R. McCabe, in particular the delineation of favourable and unfavourable disposal zones/regions. D. Barchyn and R. Dubreuil reviewed the regional stratigraphy and hydrogeology and supplied additional data for the Maples disposal project.

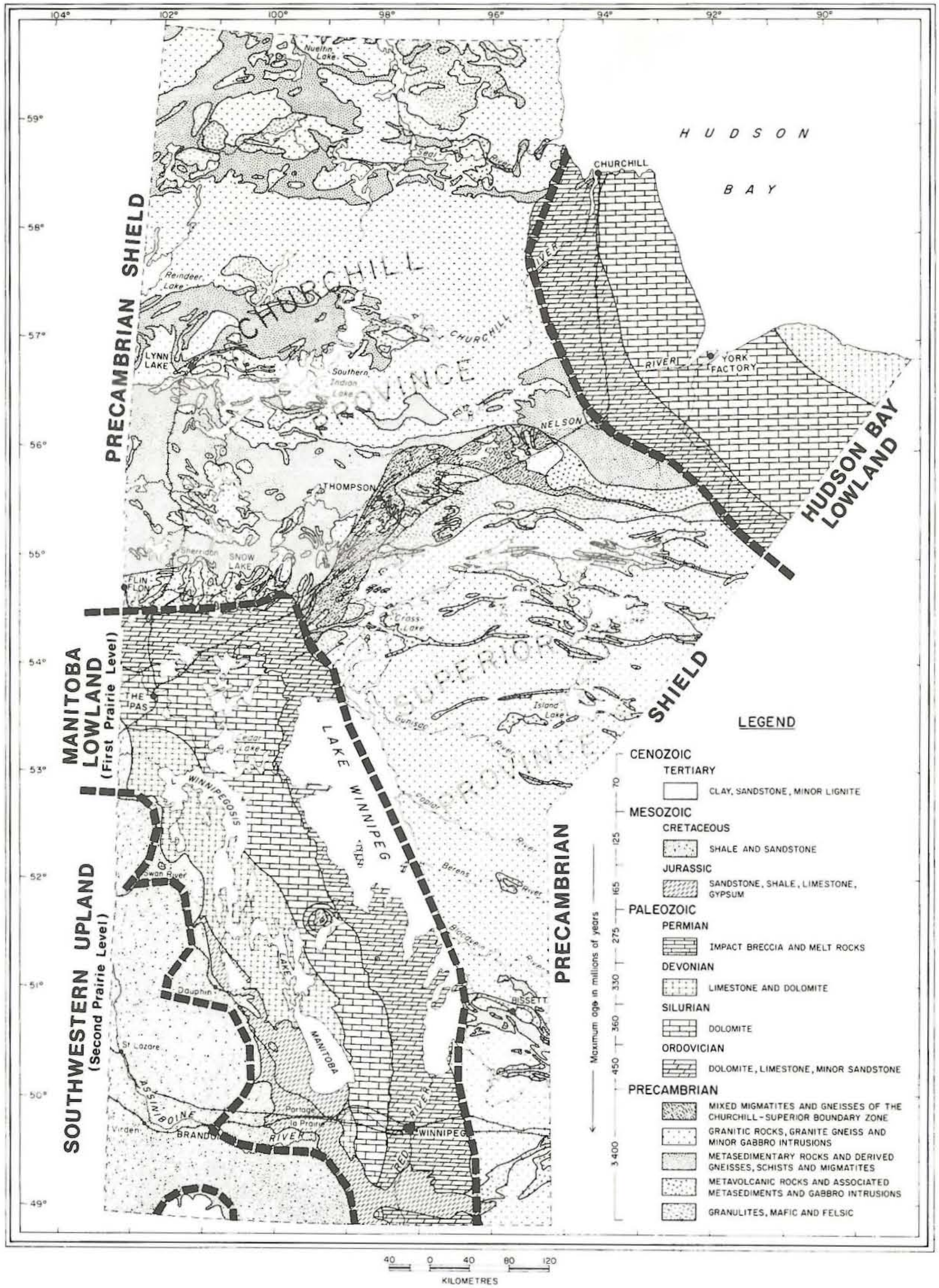



*Figure 4 Geology and physiographic regions of Manitoba.*

# 2.0 REGIONAL SETTING

### 2.1 General Statement

Subsurface strata with suitable reservoir characteristics and potential for receiving fluid industrial wastes occur in two main areas in Manitoba:

(1) the southern part of the Hudson Bay Basin region of northeastern Manitoba where up to 900 m of Ordovician, Silurian and Devonian strata occur below the surface onshore; and

(2) the northeastern part of the Williston Basin region in southwestern Manitoba where beds ranging in age from Cambrian to Tertiary attain a maximum thickness of about 2300 m in the southwestern corner of the Province.

The potential of these regions for subsurface waste disposal is based on the general criteria outlined by van Everdingen and Freeze (1971) and summarized in Table I. Adequate thicknesses of sedimentary strata are present. The regions are generally believed to be free from major faulting or folding, although local structural features are present in southwestern Manitoba, and geologic data are sparse for the Hudson Bay area. No seismic activity has been reported from either region (Simpson and Dennison, 1975). Regional hydrodynamics pose some problems in southwestern Manitoba, as will be discussed in detail in a later section, but are generally favourable. In the Hudson Bay region, the stratigraphic isolation of the basin suggests that hydrodynamics should pose no major problem.

The Hudson Bay Basin region consists of sparsely settled, poorly drained, tree- and muskeg-covered lowland, accessible for ground travel only during the winter freeze-up. The area, together with the neighbouring onshore region of northern Ontario and the basin proper in Hudson Bay, is regarded as having significant potential for petroleum exploration (Sanford and Norris, 1973). As of 1980, however, only three oil test wells had been drilled in the Manitoba part of the region and only traces of hydrocarbon were noted in one of these wells. Although this remote region has potential for development of waste-injection systems, the need for such facilities is not foreseen at present.

The Williston Basin region of southwestern Manitoba is characterized by an agriculture-based economy throughout much of the area, an oil-producing region in the southwestern corner, and a diversified industrial economy in the general Winnipeg area. Subsurface disposal of wastes, as currently practised in Manitoba, is restricted to southwestern Manitoba (Fig. 8). This part of the Province has considerable undeveloped potential for new subsurface-disposal operations, in that the thick sedimentary sequence incorporates a wide variety of structural/stratigraphic-trap configurations which might constitute disposal sites. Furthermore, southern Manitoba's expanding industrial economy provides a potential source of fluid wastes for deep-well injection. Should southwestern Manitoba become a potash-producing district, subsurface disposal of waste brines would assume considerable importance.

### 2.2 Physiography

Manitoba occupies a total area of some 650 000 km$^2$ and is divisible into four main physiographic regions (Fig. 4), each characterized by features which reflect the nature of the underlying bedrock (Davies et al., 1962), and consequently define distinctly different hydrogeologic zones or regions;

(1) the Southwestern Upland, or Second Prairie Level is an eastward extension of the Great Plains region, and occupies an area of approximately 60 000 km$^2$ in the southwestern part of the Province. The area is characterized by undulating relief and includes Manitoba's highest point, Baldy Mountain, which reaches an elevation of 832 m above sea level. The region is underlain by Mesozoic clastic rocks capped by glacial deposits that in places attain thicknesses of up to 300 m. Its eastern limit is defined by the Manitoba Escarpment, which marks the approximate eastern edge of the dominantly argillaceous Cretaceous formations;

(2) the Manitoba Lowland, covering approximately 125 000 km$^2$ is bounded to the west by the Manitoba Escarpment and to the north and east by the Precambrian Shield. Relief is subdued and elevations range from about 218 m to 275 m above sea level. Lakes Winnipeg, Manitoba, Dauphin and Winnipegosis are found within this Lowland area, and much of the land is poorly drained. The Lowland is underlain for the most part by Paleozoic carbonate strata ranging in age from Ordovician to Upper Devonian;

(3) the Precambrian Shield occupies an area of approximately 390 000 km$^2$. Elevations range from 218 m to as much as 506 m above sea level. The region is characterized by a relatively flat, hummocky surface with local relief rarely exceeding 30 m. Swamps and lakes are widespread, but Precambrian rocks are exposed in many parts of the area. Drainage is typically highly disrupted in most areas;

(4) the Manitoba part of the Hudson Bay Lowland occupies an area of 75 000 km$^2$ flanking the southwestern shore of Hudson Bay; it is a poorly drained area of low relief, underlain by a Paleozoic sequence consisting dominantly of carbonates.

Drainage for all of Manitoba is into Hudson Bay. The Province's major southern rivers (Winnipeg, Assiniboine, Red and Saskatchewan) flow into Lake Winnipeg, which in turn is drained by Nelson River into Hudson Bay. Churchill River drains the northern part of the area, and also flows into Hudson Bay. Recently, a considerable part of the flow of Churchill River has been diverted to Nelson River, to feed the series of major hydro-electric projects being installed along the Lower Nelson.

### 2.3 Regional Stratigraphy

The stratigraphic succession of the southwestern part of the Hudson Bay Basin region (Fig. 5) comprises two main sequences of limestones, dolomites and minor evaporites. These sediments are Middle Ordovician to Middle Silurian, and Lower to Middle Devonian in age, respectively. The two dominantly carbonate sequences are separated by a dominantly clastic sequence of Upper Silurian through Lower Devonian fine grained red beds, dolomites, and subordinate evaporites (Sanford and Norris, 1973).

Considerably greater lithologic variation is encountered in the Williston Basin region of southwestern Manitoba (Fig. 5), where the succession is characterized by three main divisions:

(1) a lower clastic division, consisting primarily of the Middle Ordovician Winnipeg Formation, which reaches a maximum thickness of about 68 m. A thin wedge of Cambrian sandstone and shale of the Deadwood Formation, up to 60 m in thickness, occurs unconformably beneath the Winnipeg Formation in the extreme southwestern corner of the Province;

(2) a Paleozoic carbonate-evaporite division, Middle Ordovician through Mississippian in age, which includes an important potash-bearing unit, the Middle Devonian Prairie Evaporite, and has a maximum thickness of about 1200 m. This sequence is conformable with the underlying lower clastic division, but is overlain with marked angular unconformity by:

(3) an upper clastic division, Triassic(?)-Jurassic through Recent in age, which consists primarily of shales with sandstone interbeds, but incorporates evaporite strata near the base and reaches a maximum thickness of about 1050 m.

Because this study is devoted primarily to an evaluation of the subsurface-disposal potential of the sedimentary strata of Manitoba, the hydrologic characteristics of the strata are deemed to be of more importance than the lithologic characteristics. Because of this, the generalized lithologic subdivisions noted above are greatly simplified from the detailed stratigraphic subdivisions shown in Figure 5. Formations

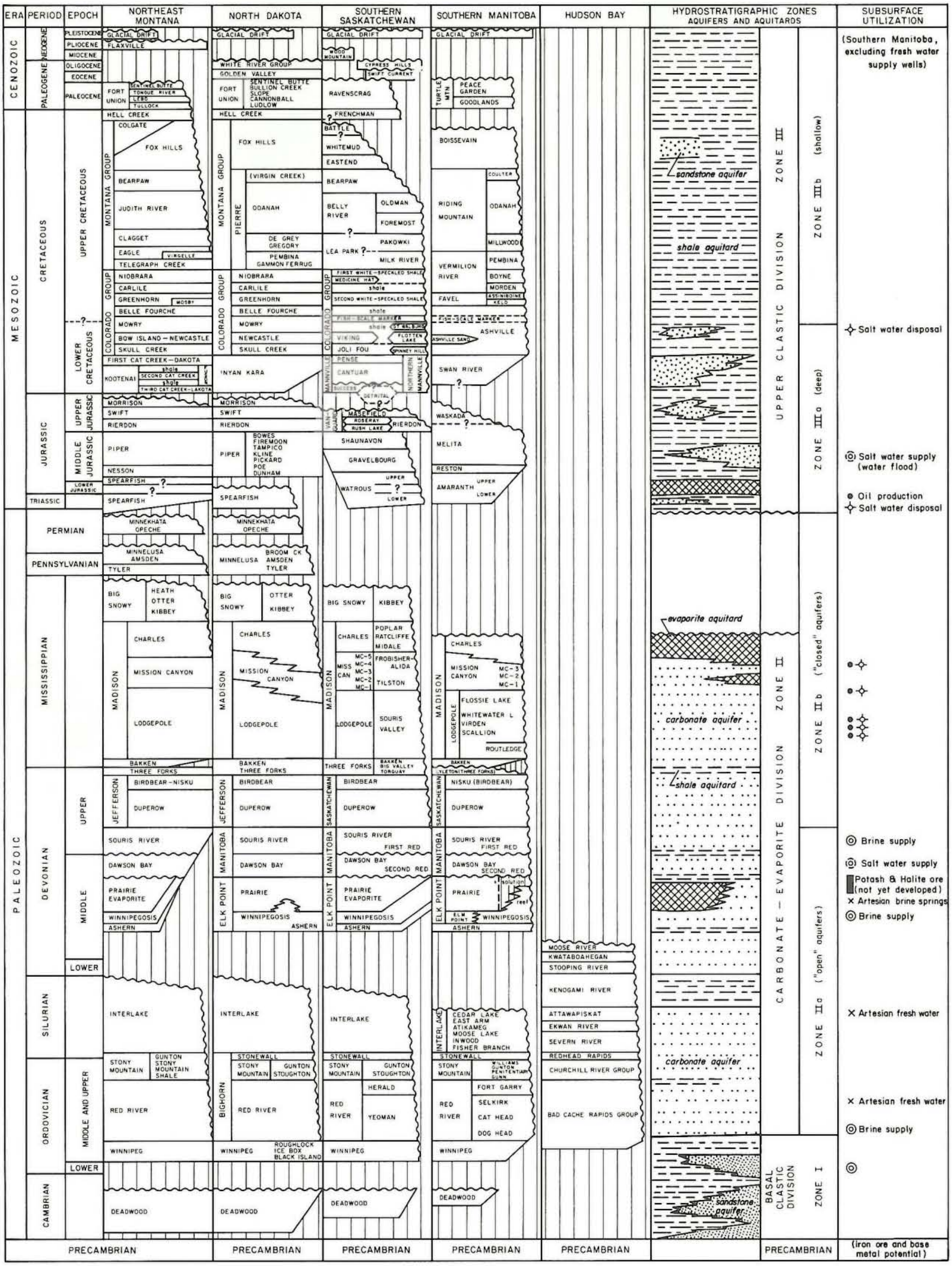


*Figure 5 Stratigraphic correlation and nomenclature chart showing current subsurface utilization and potential disposal aquifers.*

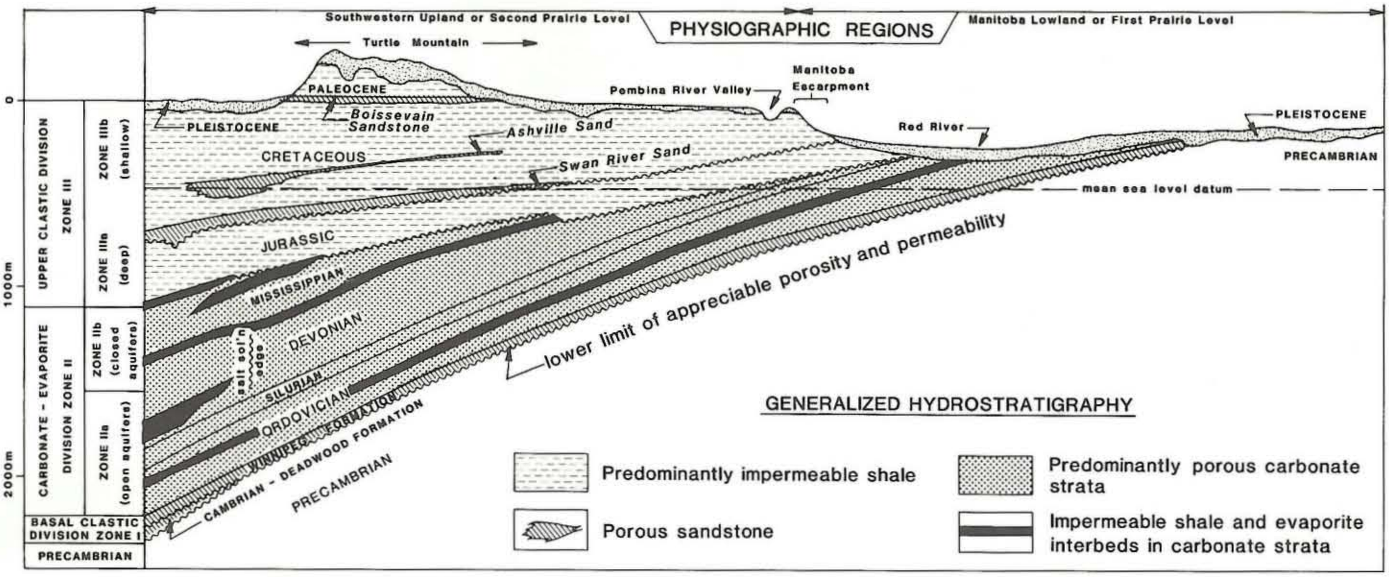



*Figure 6 Geologic cross-section, southwestern Manitoba along Manitoba-North Dakota border. Vertical exaggeration approximately 50:1.*

cannot generally be considered as hydrogeologically distinct units, because of varying degrees of actual or potential cross-formation fluid flow. The generalized subdivisions used in this report are considered to be more or less hydrogeologically distinct units, although some degree of aquifer separation is evident within these gross units, particularly in the deeper parts of the basin. The principal hydrogeologic barriers or aquicludes (evaporite and shale beds) are indicated in Figures 5 and 6. Detailed stratigraphic studies for the Hudson Bay area have been presented by Cumming (1975), Norford (1971), and Sanford and Norris (1975), and for southwestern Manitoba, by Baillie (1949, 1950, 1951 and 1953); Stearn (1956); Wickenden (1945); Stott (1955); Bannatyne (1959, 1960, 1970, 1971 and 1975); Porter and Fuller (1959); Andrichuk (1959), and McCabe (1959, 1963, 1967, 1971 and 1978).

Detailed stratigraphic features relevant to disposal potential are discussed in a later section.

### 2.4 Regional Structural Framework

The Phanerozoic succession of the Hudson Bay region occupies two sedimentary and structural basins: Moose River Basin in the south, and Hudson Bay Basin in the north, separated by the northeast-trending Cape Henrietta Maria Arch. Although data are sparse, the regional northeasterly basinward dip in the Manitoba portion of Hudson Bay Basin appears to be relatively uniform, increasing from about 2 m/km at the edge of the basin to about 7 m/km in the most basinward onshore area. A prominent Precambrian inlier in the Churchill area indicates the presence of at least one major Precambrian paleotopographic high, with paleotopographic relief of possibly as much as 250 m, but limited well data south of Churchill show no evidence of any other such features.

The dominant structural element in southern Manitoba, as delineated by structure contours on the Precambrian basement (Fig. 7), is a homocline characterized by a gradual increase in the dominantly southwesterly dip from 2.2 m/km near the perimeter of the Shield to 9.2 m/km in the southwestern corner of the Province. The strike is north to northwest near the Forty-Ninth Parallel, but north of Grand Rapids (approximately Tp. 58) undergoes a marked swing to the west. The southwesterly increase in dip of the basement marks, in a very general way, the passage from a stable tectonic shelf, to the northeastern flank of Williston Basin proper. In detail, however, the tectonic framework of the basin changes markedly for different stratigraphic intervals (McCabe, 1967).

Superimposed on the uniform southwesterly regional dip are a considerable number of mostly small-scale structural features that generally affect only a portion of the sedimentary succession, and may not be evident on the basement contour map. Such structures can have serious implications for subsurface-disposal potential in local areas. These structures relate to a number of different factors: salt collapse, crypto-explosion (meteorite impact?) events, differential compaction, erosional relief at major unconformity surfaces, and true tectonically based structures. The origin and distribution of these local structures are discussed in detail in a later section.

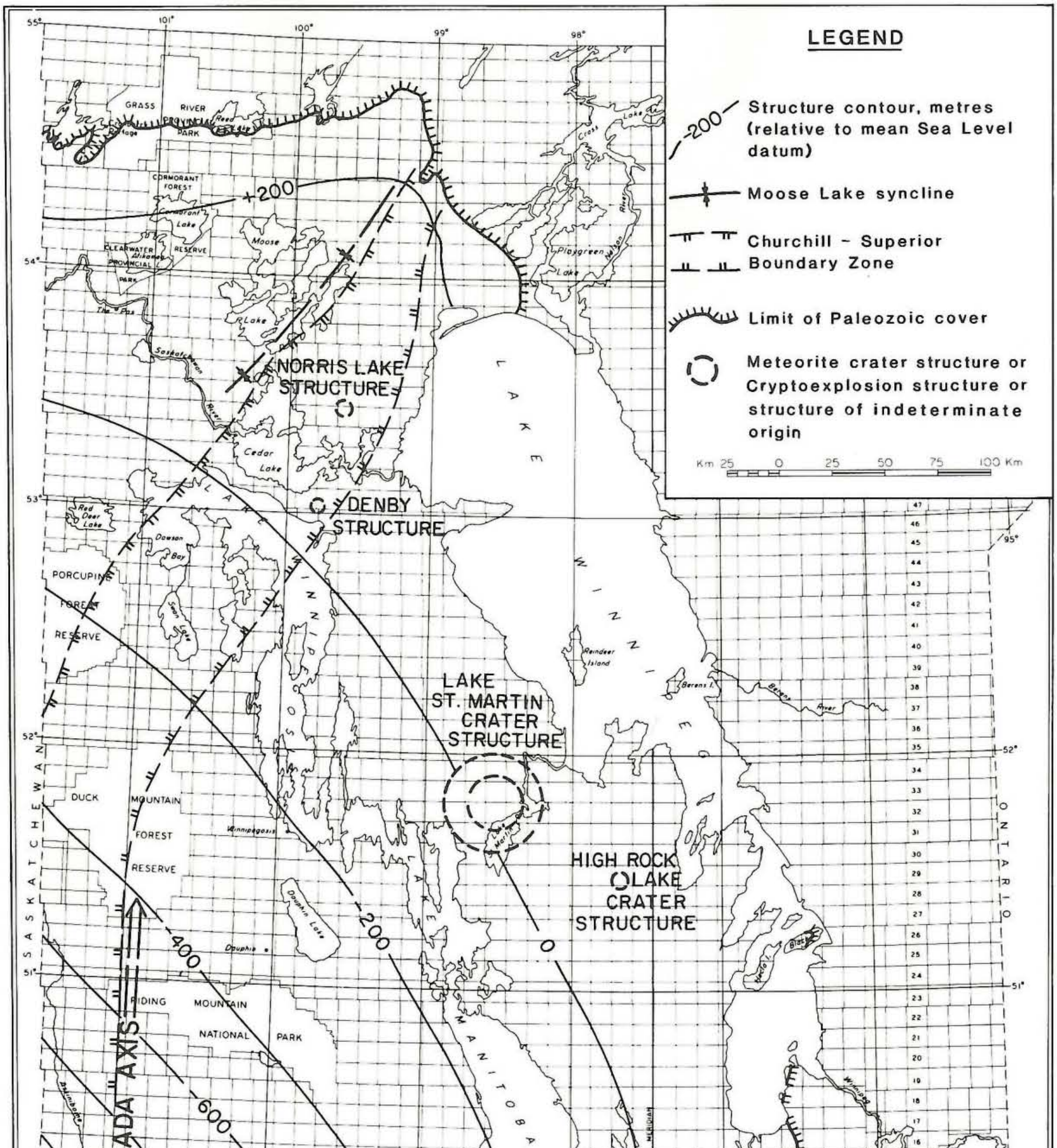



*Figure 7 Structure contour map, Precambrian basement, southwestern Manitoba.*

# 3.0 REGIONAL HYDROGEOLOGY

### 3.1 General Statement

Groundwater flow and geochemistry are important considerations when assessing the suitability of sites for deep-well waste disposal. Because fluid wastes introduced into the hydrogeologic environment of a geologic basin tend to assume the vector properties of the groundwater regime, waste injection operations should not be initiated without a knowledge of formation-fluid flow within the principal hydrostratigraphic units. Before presenting a detailed description of the structure and stratigraphy of potential disposal strata in Manitoba, it is thus necessary to discuss the broader aspects of regional, basinwide flow systems, and show how these systems relate to Manitoba. Ideally, there should be no movement of formation fluids so that any waste emplaced in these fluids would tend to remain in place permanently. Such stagnant or quasi-stagnant conditions, however, are relatively scarce and restricted in extent.

### 3.2 Regional Movement of Formation Fluids

Mathematical models of groundwater movement, developed by Toth (1962, 1963) and Freeze and Witherspoon (1967), indicate that the distribution of fluid potential and related patterns of fluid flow are strongly influenced by topography and geology. The importance of these factors in controlling fluid-potential distribution (i.e. fluid flow) in the Western Canada Sedimentary Basin as a whole has been demonstrated by Hitchon (1969a, 1969b). The overall flow pattern is from southwest to northeast, on a basinwide scale, and is largely controlled by the reservoir characteristics of the major hydrostratigraphic units, which generally show widespread lithlogic and hydraulic continuity in the northern Williston Basin region. In southern Saskatchewan, northeastward movement of water in Paleozoic strata, accompanied by solution of Devonian (Prairie Evaporite) salt beds, was reported by Milner (1956).

It seems likely that Paleozoic formations in Manitoba have been, and presently are being, subjected in some degree to such basinwide flow systems. However, regional salinity data presented by Hitchon (op. cit.) and by Simpson and Dennison (1975) show that relatively high salinities occur in the area of southeastern Saskatchewan and the southwestern corner of Manitoba, suggesting that this area may have been relatively isolated from any regional flow system.

### 3.3 Groundwater Discharge and Recharge — Manitoba Outcrop Area

All major river valleys of the Saskatchewan-Nelson drainage basin constitute important groundwater discharge areas for meteoric waters as well as for the previously noted regional subsurface flow systems (Hitchon, 1969a). Formation brines from deeper basinal areas are discharged from outcropping Paleozoic carbonate strata along much of the northeastern margin of the Western Canada Basin, both as springs and as diffuse seepages over large areas. Saline-spring discharge has been recorded from locations along the southern perimeter of the Precambrian Shield in eastern Alberta (Souther and Halstead, 1969), east-central Saskatchewan (Simpson and Dennison, 1975) and western Manitoba (Bannatyne, 1960; van Everdingen, 1971). In particular, carbonate mounds of the Devonian Winnipegosis Formation (McCabe, 1967), occurring near surface along much of the western shore of Lake Winnipegosis are the sites of extensive brine discharge in Manitoba (Fig. 10). Diamond drilling has encountered high artesian heads (up to 12 m above land surface) in the Winnipegosis aquifer.

Typical compositions of Manitoba brine springs are shown in Table II. According to van Everdingen (1971), brines from pre-Devonian units also contribute to the saline waters discharged in this area. This discharge probably represents a continuation of the regional fluid flow and associated salt solution that was first initiated in late Devonian time and has recurred intermittently up to the present. The principal times of salt solution and attendant collapse are outlined in Table III. Christiansen (1970) has delineated Recent salt collapse features in Saskatchewan, indicating that regional formation fluid flow, with attendant salt solution, is taking place at the present time.

Most formation salinity maps (Fig. 9, 11) show a decrease in salinity towards the outcrop belt, with relatively fresh, potable water in most near-surface aquifers. Replenishment of fresh water in these shallow bedrock aquifers of southern Manitoba is for the most part by local introduction of meteoric waters, which seep downwards through glacial deposits overlying the aquifers, and penetrate downdip for some distance from the outcrop belt. The Saskatchewan-Nelson Basin Board (1972b) lists 5 main groundwater flow systems (Fig. 8) within the Paleozoic carbonate aquifer underlying the Manitoba Lowlands, or originating outside the aquifer but of importance for recharge or for effect on water quality:

(1) a major flow system originates in a high, sandy area east of the Red River with flow toward the river;
(2) another flow system originates in the Birds Hill area, northeast of Winnipeg;
(3) to the northwest of Winnipeg, a system extends from the Lake Manitoba-Lake Winnipeg divide toward Winnipeg and the Red River;
(4) in the area between Lakes Manitoba and Winnipeg, groundwater flow in the upper part of the aquifer is from the divide toward the lakes;
(5) in the vicinity of The Pas, groundwater flow in the aquifer is southward in the direction of the Saskatchewan River.

A knowledge of the flow regimes noted above is important since any subsurface waste contamination would eventually become involved in one of these surficial flow systems.

### 3.4 Formation Salinity Maps

From the foregoing, it is evident that areal variation in the salinity of formation fluids can provide a basis for estimating the extent of regional fluid flow in subsurface aquifers. Salinity maps for selected reservoir zones are therefore included in the following stratigraphic discussions. In general terms, the significance of the salinity maps, with respect to subsurface waste-disposal potential, is that the areas of highest salinity probably reflect the greatest degree of separation or isolation of the aquifer from the near-surface groundwater flow regime. This generalization must be used with caution, however. For instance, relatively high salinities noted for Winnipegosis strata close to the outcrop belt are not indicative of hydraulic isolation of the Winnipegosis, but just the opposite. The Winnipegosis Formation shows a high rate of regional formation-fluid flow resulting in direct discharge of saline brine to surface in the form of salt springs. The high near-surface salinity results because the updip flow rate of brine is so high (relatively) that the diluting effects of meteoric waters are limited.

Salinity maps also are useful in evaluating the economic potential of the formation brines, since the brines of highest salinity can be utilized commercially. For further details on the salinity of formation fluids, and also reservoir quality, the reader is referred to the following Mineral Resources Division publications:

Table of Lower Paleozoic Formation Water Analyses.

Table of Lower Paleozoic Drill Stem Tests and Oil and Gas Shows.
Additional formation fluid data for Mississippian and younger strata are available on open file at the Petroleum Branch.

## TABLE II

### CHEMICAL COMPOSITION OF BRINES IN SALINE SPRINGS, SOUTHERN MANITOBA

Analyses — parts per thousand

| Sample | A1 | A2 | B1 | B2 | C | D | F | G | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| K | 0.095 | 0.136 | 0.352 | 0.231 | 0.113 | 0.009 | 0.011 | 0.006 | 0.071 | 0.003 | 0.045 | 0.459 |
| Na | 20.710 | 18.529 | 22.191 | 21.629 | 20.406 | 10.223 | 18.716 | 19.413 | 12.107 | 8.863 | 15.181 | 15.470 |
| Ca | 1.325 | 1.159 | 1.424 | 1.443 | 1.200 | 0.600 | 1.134 | 1.185 | 0.855 | 0.718 | 0.976 | 1.074 |
| Mg | 0.316 | 0.301 | 0.351 | 0.345 | 0.304 | 0.195 | 0.343 | 0.329 | 0.212 | 0.240 | 0.504 | 0.292 |
| Fe + Al | 0.006 | 0.005 | Traces | 0.003 | 0.110 | 0.009 | 0.004 | 0.005 | 0.006 | 0.006 | 0.004 | 0.005 |
| $SO_4$ | 3.085 | 2.749 | 3.229 | 3.243 | 2.993 | 1.646 | 2.600 | 2.678 | 2.123 | 1.732 | 2.695 | ..... |
| Si | 0.004 | 0.004 | 0.002 | 0.009 | 0.004 | ..... | ..... | ..... | ..... | ..... | ..... | ..... |
| Cl | 34.340 | 30.460 | 35.620 | 35.280 | 34.240 | 16.340 | 29.080 | 29.600 | 18.240 | 14.800 | 20.650 | 25.660 |
| Br | 0.108 | 0.056 | 0.107 | 0.080 | 0.041 | Traces | 0.015 | 0.022 | 0.018 | 0.027 | 0.015 | ..... |
| I | Nil | Nil | Nil | Nil | Nil | Nil | Nil | Nil | Nil | Nil | Nil | ..... |

Supplemental analyses for (K) (in parts per *billion*): Pb 35.73; Ag 0.68; Zn 24.96

Cd 0.27; Cu 29.88; Ni 9.69; Mn 2.33; F 927.24.

Sample locations:

A) 33-43-24W; Bell River Bay
B) 23-44-24W; Salt Point
C) 17-44-24W; " "
D) 11-44-25W; Steeprock River
F) 18-45-26W; " "
G) 11-45-26W; Red Deer River
H) 2-38-20W; Camperville
i) 1-35-20W; "
J) 21-32-18W; Red Deer Point
K) Average of 47 analyses, Dawson Bay-Winnipegosis area

Analyses A-J from Cole (1915); analysis K from Evans, 1977, Manitoba Mineral Resources Division, open file report

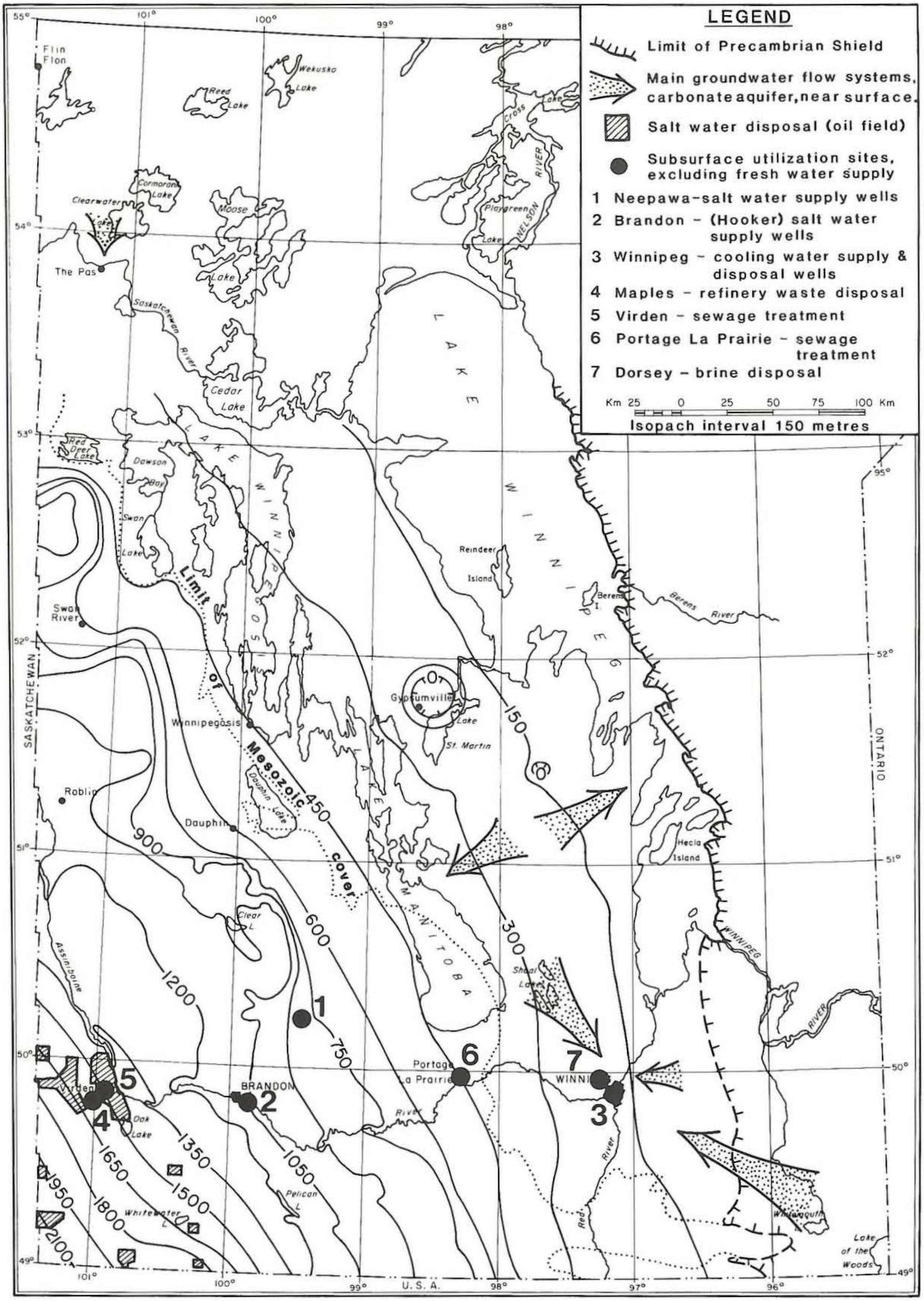



*Figure 8 Isopach map, total Phanerozoic, southwestern Manitoba, showing subsurface disposal sites and principal near-surface groundwater flow systems*

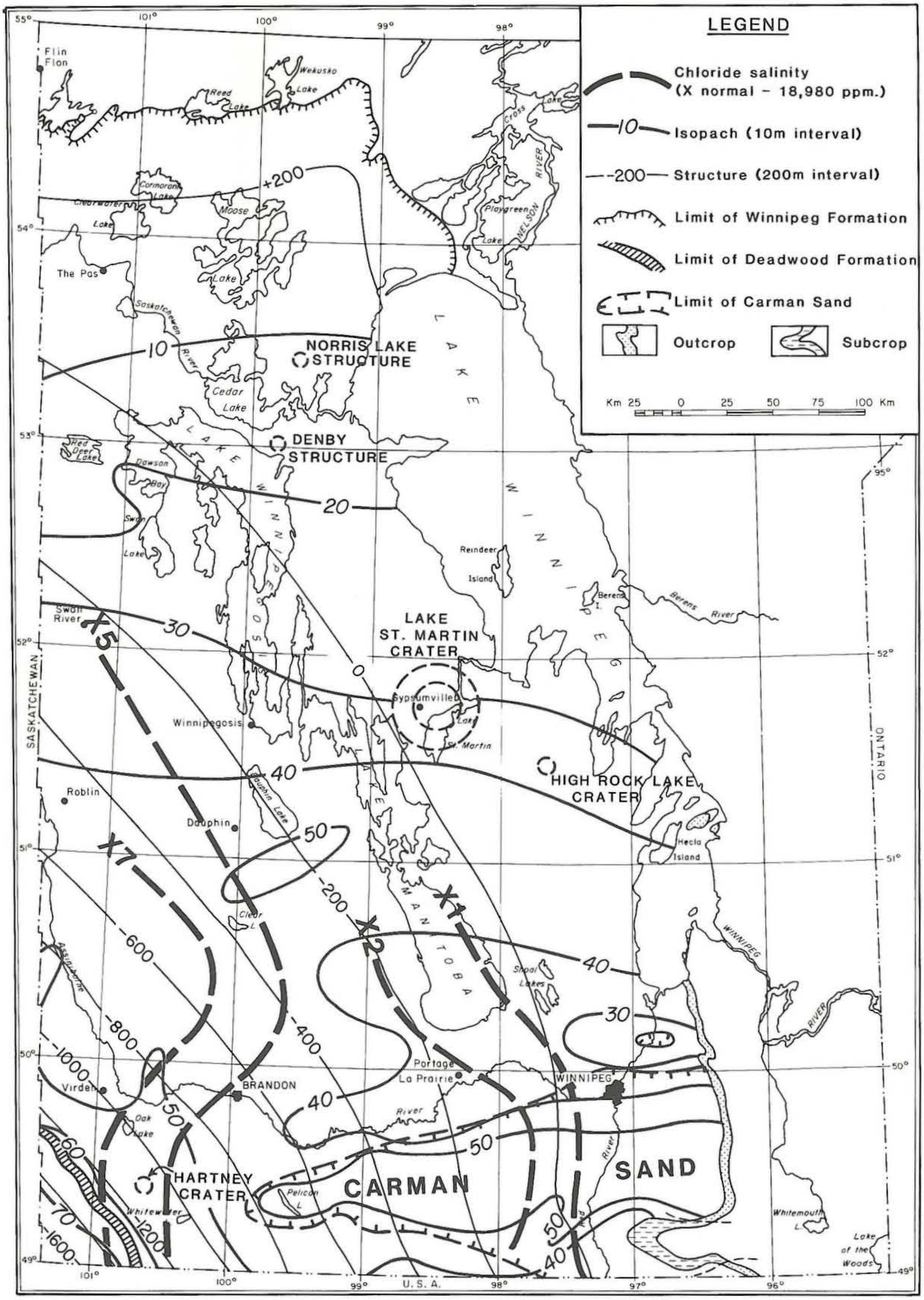



Figure 9 Isopach-structure contour and salinity map, basal clastic unit, southwestern Manitoba.

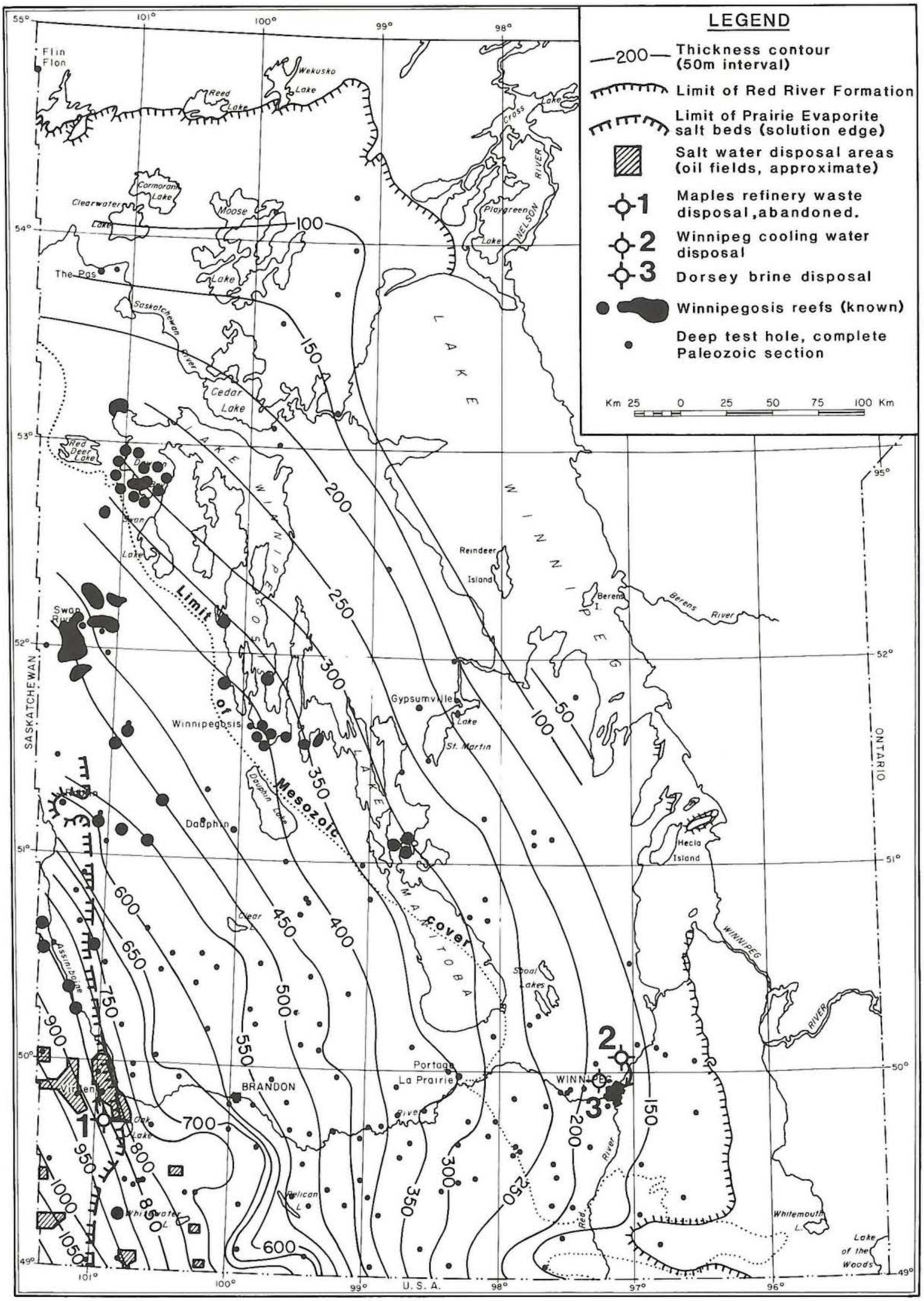



*Figure 10 Isopach map, carbonate-evaporite unit, southwestern Manitoba.*

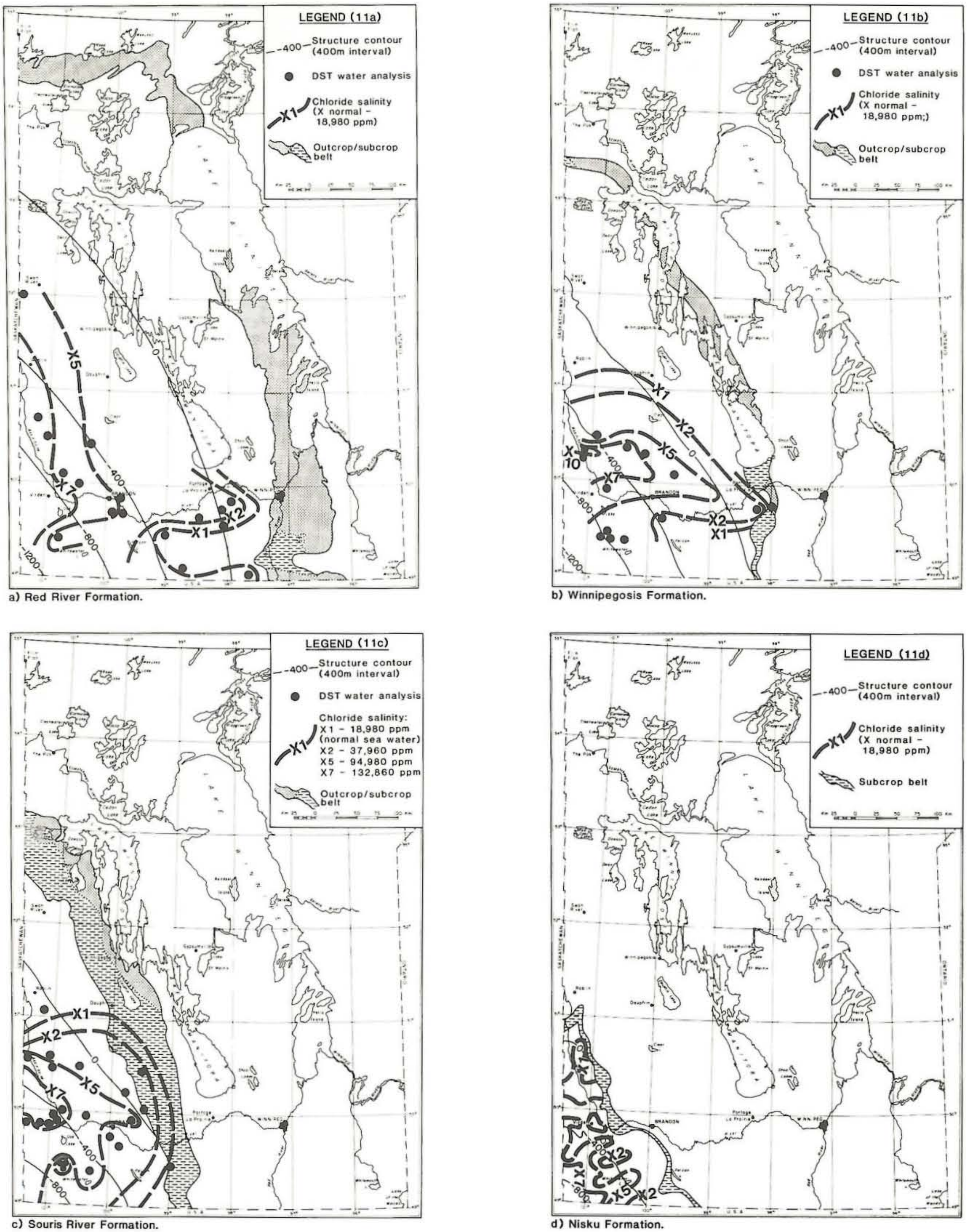



*Figure 11 Salinity maps for selected formations, carbonate-evaporite unit, southwestern Manitoba.*

# 4.0 DETAILED STRUCTURAL GEOLOGY

### 4.1 General Statement

In any evaluation of the subsurface-disposal potential of a region or area, the local and regional structural configuration is of considerable importance. Any type of structural deformation, resulting from tectonic movement, from stratigraphically related factors (salt collapse, differential compaction), or from other factors (meteorite impact?), can give rise to faulting and fracturing that may permit vertical migration of formation fluids across otherwise impermeable stratigraphic barriers.

The regional structural framework for the Hudson Bay area has been noted previously, and will not be discussed further because of lack of detailed structural data. The relatively uniform structural framework for southwestern Manitoba has been indicated as generally favourable for subsurface disposal, but closer examination shows a considerable number of local structural anomalies, all of which are to some degree detrimental to the local subsurface-disposal potential. The various types of structures and their known occurrences are therefore discussed in detail prior to a general evaluation of the potential for subsurface disposal of liquid industrial wastes.

### 4.2 Structural Anomalies Affecting Precambrian Basement

The gentle and relatively uniform southwesterly dip of the Precambrian basement (Fig. 6) is a reflection of the topographic relief on the erosion surface prior to deposition of the lowermost Paleozoic strata, as well as all subsequent tectonic subsidence. As noted by McCabe (1967, 1971), the Precambrian erosion surface generally is flat. However, several local anomalous features disrupt a gentle southwesterly dip (Fig. 7).

(1) The Moose Lake syncline located northwest of Lake Winnipeg is defined by a northeast-trending flexure of structure contours on the basement. The feature is also defined by a northeasterly deflection of the Ordovician and Silurian outcrop belts, indicative of a post-Silurian age for the structural deformation. The flexure coincides with the trend of prominent, basement-derived gravity and magnetic anomalies, which mark the continuation beneath the Phanerozoic cover of the boundary zone between the Precambrian Churchill and Superior provinces. The southern extension of this trend is termed the Birdtail-Waskada Axis (McCabe, 1967) and is the site of numerous structure and isopach anomalies in the overlying Phanerozoic succession, related at least in part to collapse attendant upon localized solution of Middle Devonian evaporite strata.

(2) A gently anticlinal flexure of the Precambrian surface extends in an east-west direction, south of Winnipeg. The axis of the flexure coincides roughly with the southern edge of the Carman Sand of the Winnipeg Formation. Differential compaction structure is evident in strata overlying the sand body.

(3) Crater (meteorite impact?) structures: A number of relatively small but extremely complex structural anomalies disrupt the uniform regional structural pattern of southwestern Manitoba, and have a major impact on the *local* potential for subsurface disposal. Three of these anomalies are crater structures, believed to be possible meteorite impact features (Fig. 7). All are characterized by extreme faulting, fracturing and brecciation.

The Lake St. Martin Crater (McCabe and Bannatyne, 1970) located in the central Interlake area is the largest crater, approximately 22 km in diameter with structural disturbance extending for about 10 km beyond the crater rim. The total area of structural disturbance is approximately 5500 $km^2$. The entire sedimentary section has been affected and Precambrian basement rocks have been uplifted by at least 215 m.

The Hartney Structure, located in southwestern Manitoba near the village of Hartney, is a subsurface feature, and structural disturbance is limited to the lower part of the Upper Clastic Unit (the Jurassic portion) and the underlying strata down to Precambrian basement. The overlying Cretaceous strata are undisturbed. The feature is estimated to be about 10 km in diameter.

The smallest of the crater structures is High Rock Lake, located in the southern Interlake area, about 50 km southeast of the Lake St. Martin Crater (Fig. 7). The structurally disturbed area is about 5 km in diameter, and all sedimentary strata in the area are highly brecciated. Precambrian rocks in the crater rim have been uplifted a minimum of 150 m (McCabe, et al. 1982).

Because of the intense structural deformation associated with the crater structures, no hydrologic isolation is possible and consequently subsurface waste disposal would not be acceptable. Furthermore, the extent of reservoir fracturing possibly extends beyond the limits of definable structural disturbance thus increasing the size of the area that would be unacceptable for waste disposal.

Other crater structures may exist in Manitoba. Two single-hole subsurface anomalies have been noted, one near Denbeigh Point and a second near Norris Lake (Fig. 7). Although the nature of these features cannot be determined from presently available data, both are characterized by anomalously high elevations of Precambrian basement, and the only other such basement anomalies are associated with presumed impact features.

Structural anomalies of the above type in southwestern Manitoba generally are hidden beneath extensive cover of younger sedimentary strata and/or glacial till. Of all of the above noted structures, only the High Rock Lake crater has some slight topographic expression, so the existence of such features can be confirmed only by test drilling.

### 4.3 Phanerozoic "Structural" Features

In addition to the tectonic, basement-related features and cryptoexplosion structures noted above, a number of other "structural" anomalies are evident in both Paleozoic and Mesozoic strata. These structures, however, are stratigraphically restricted and result from depositional anomalies and post-depositional adjustments within the Phanerozoic succession rather than tectonic activity.

#### 4.3.1 Solution-generated collapse structures

Local, stratigraphically restricted structural lows (or highs) are the result of one or more episodes of solution of Middle Devonian evaporite beds (Prairie Formation) with resultant collapse of overlying strata. Ages of such structures range from Upper Devonian to Recent (Table III). Structures may be fault- or fracture-bounded. In places, the collapsed strata maintain their stratigraphic integrity, with only minor fracturing; elsewhere, a chaotic polymict collapse breccia has formed. Salt collapse structures are probably the single most important anomaly affecting the quality of subsurface disposal sites. A discussion of the mode of origin of these features is presented later.

#### 4.3.2 Reef-controlled structures

Numerous Middle Devonian Winnipegosis reefs or mounds occur in a north-trending belt coincident with the Birdtail-Waskada Axis, and also as isolated features as far east as Lakes Winnipegosis and Manitoba (Fig. 10). In areas of salt solution, as noted above, the collapsed strata may be draped over underlying Winnipegosis reefs so that the configuration of the collapsed strata mimics the paleotopography of the underlying reef surface.

#### 4.3.3 Differential compaction structures

Positive relief features on the Precambrian erosion surface can give rise to differential compaction structures in the overlying strata. Simpson and Dennison (1975) note such features in Saskatchewan, but to date none have been identified in Manitoba. Differential compaction structures also can be associated with erosional features at the sub-Mesozoic unconformity. Differential compaction also has occurred in association with large, sharply defined sand bodies such as the Carman Sand in the Ordovician Winnipeg Formation (Fig. 9), and the Ashville Sand in the Lower Cretaceous Ashville Formation (Fig. 12).

#### 4.3.4 Reactivated Precambrian features

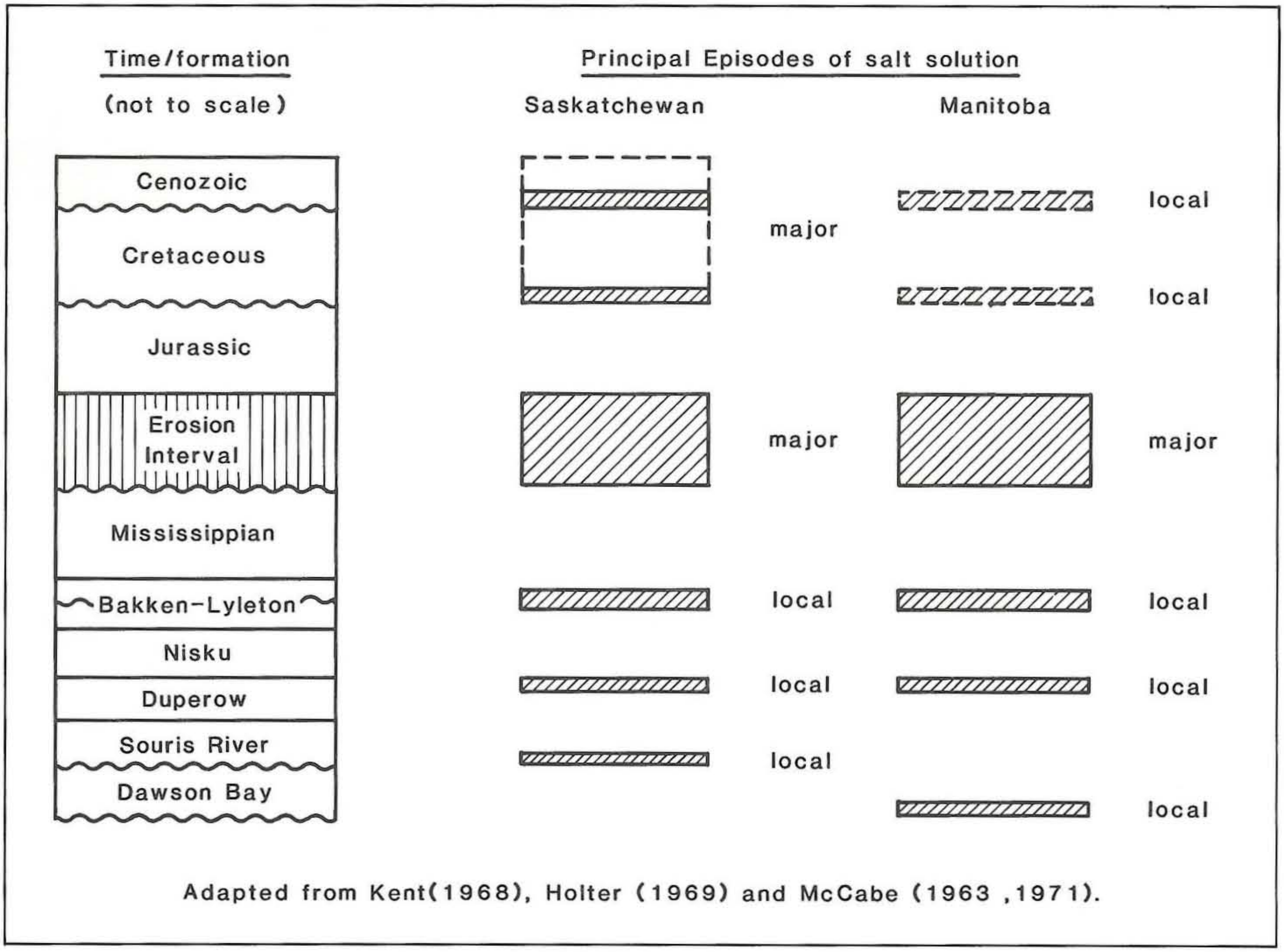
Reactivation of Precambrian structural features during Phanerozoic time may have exerted an important influence on the overlying rocks in the form of both structural and stratigraphic (isopach/lithofacies) anomalies affecting deposits of Ordovician through Holocene age. Of particular importance is the belt of both early and late salt collapse structures, and the depositional edge of the Winnipegosis fringing bank, both of which coincide with the subsurface extension of the Precambrian Churchill-Superior boundary zone, or Birdtail-Waskada Axis (Fig. 7). Available data, although admittedly sparse, give no evidence of any coincident structural anomaly on the Precambrian basement indicating that the basement involvement is subtle and probably limited to gentle flexing, rather than any positive displacement features. McCabe (1971) has suggested that the Manitoba portion of the Williston Basin underlain by the Superior crustal block may have undergone relatively greater subsidence during periods of deposition, compensated by correspondingly greater uplift during periods of erosion. No net structural displacement would result from such cyclical movements.

### 4.4 Origin of Solution-generated Collapse Structures

Because of the widespread distribution of salt collapse structures and their importance in estimation of subsurface disposal potential, a brief outline of the types and modes of origin of such features is warranted. Salt collapse structures are related to solution of the salt and potash beds of the Devonian Prairie Evaporite, with resultant collapse of the overlying strata. Near the Saskatchewan border evaporite thicknesses are in the order of 120 m and overlie a thin interreef sequence of Winnipegosis dolomites. To the east, however, at approximately range 25 WPM (Fig. 10), the salt beds pinch out abruptly, coincident with a pronounced, but lesser (50 m), thickening of the Winnipegosis Formation. A thin blanket of anhydritic evaporite extends eastward, over the thicker but relatively uniform Winnipegosis section.

The edge of the Devonian salt beds probably is the result of salt solution. Up to 80 m of salt have been removed from the area east of the present salt edge. Figure 14 shows a conservative estimate of the original eastward extent of the Prairie Evaporite salt beds and the probable area of salt solution. This entire solution area probably has been

**TABLE III**
**INTERVALS OF ACCELERATED SOLUTION-REMOVAL OF BEDDED SALT AND ATTENDANT COLLAPSE OF OVERLYING STRATA, NORTHERN WILLISTON BASIN REGION.**



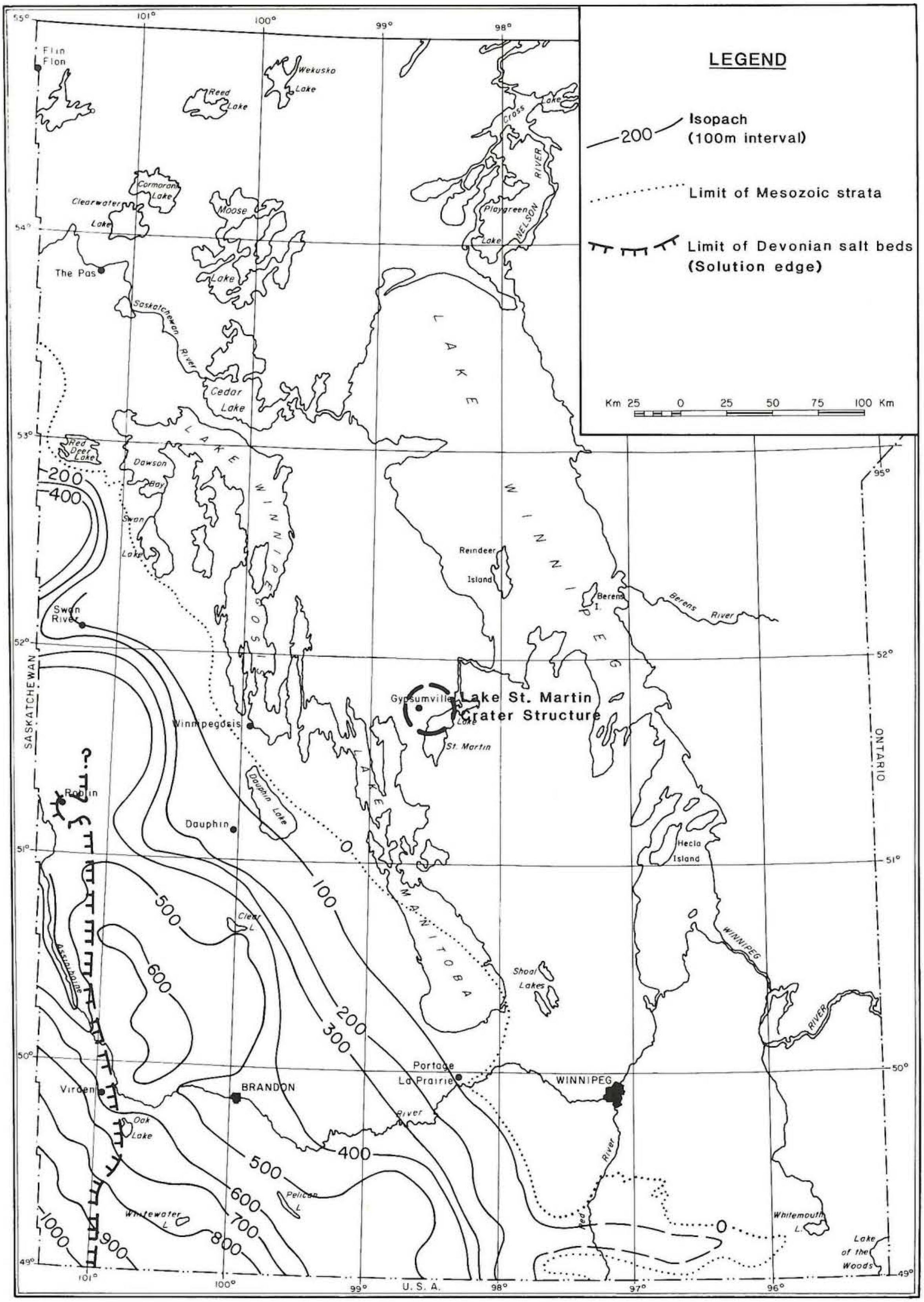



Figure 12 Isopach map, upper clastic unit, southwestern Manitoba.

subjected to some degree of salt collapse, and hence some degree of fracturing, faulting or disruption can be expected in post-Winnipegosis strata. These strata must therefore be considered suspect, if not unfavourable, for waste disposal.

Within the present limits of the Prairie Evaporite salt beds a large number of generally small-scale collapse structures can be identified (McCabe, 1963) (Fig. 10). These structures show a wide range in age. Kent (1968) and Holter (1969) summarized evidence for solution removal of salt in Saskatchewan during several discrete intervals from late Middle Devonian to late Cretaceous or Early Tertiary time. Simpson (1978b) outlined the main characteristics of solution-generated collapse structures in the northern Great Plains region, together with their probable modes of origin, and suggested how these features might be related to plate interactions along the western continental margin. In Saskatchewan the earliest solution events (Table III) associated with the previously noted basinwide groundwater flow system gave rise to local channels which later coalesced to form the present edge of the Prairie Evaporite, along the main solution channel in central Saskatchewan.

In Manitoba, a comparable series of solution episodes seems to have occurred although documentation is less precise because solution has occurred largely along the edge of the Prairie Evaporite rather than within the evaporite area. It is therefore difficult to distinguish between salt solution and depositional thinning of the salt beds. Although salt solution in Manitoba, at least along the eastern edge of the salt basin, does not seem to be *geologically* related to the main central-basin groundwater flow system of central Saskatchewan, the similarity in timing of local collapse events in the two areas suggests that the same (tectonic?) events that controlled the periodic solution of salt beds in Saskatchewan also affected the subsurface flow systems in Manitoba.

The earliest known periods of salt solution in Manitoba are referable to Dawson Bay(?), Duperow, and Bakken-Lyleton times (Middle Devonian to Early Mississippian), and are evidenced by local thickening of these formations (McCabe, 1971). Although some solution-related structures are synclinal in nature, some of the early collapse events give rise to positive structural features, the so-called "sombrero structures". These structures result from early multiple-stage salt solution. For example, in the Waskada area of Manitoba (Tp. 1, Rge. 25W) early solution occurred during Duperow and Bakken/Lyleton times. This is indicated by local depositional thickening of these strata in the area of *initial* collapse. Later, in post-Mississippian pre-Jurassic time, salt was removed from the surrounding area, resulting in collapse and thickening of adjacent Mississippian strata at the unconformity surface. The result is a local, stratigraphically confined, "structural" high in the area of initial collapse. Truncation of the structure at the Mississippian unconformity surface has resulted in formation of a window of MC-1 strata within the outcrop belt of the younger MC-3 beds (Fig. 5, 14). No structure is evident below the Duperow Formation, which was laid down during the time of earliest solution.

Although a number of early salt collapse structures can be defined, most salt collapse structures in Manitoba are relatively late, post-Mississippian in age, and are truncated at the sub-Mesozoic unconformity, indicating that solution occurred during the period of major, basinwide, late Paleozoic to early Mesozoic uplift and erosion. Local thickening of basal Mesozoic red beds along some structures indicates that solution, in these areas, occurred very late in the erosional period. Local thickening of younger Jurassic and Cretaceous strata in a few localities indicates still later periods of solution. McCabe (1963, Fig. 12) shows a timetable of structural development (solution) for the small, sharply defined, linear structural lows in the Daly-Virden oil-producing area. Some of these features show distinctly different ages along a single, small continuous structure.

The mechanics of the salt solution process in Manitoba are not clearly defined. In one area of partial salt collapse, preservation of a normal sequence in the upper part of the Prairie Evaporite indicates that limited solution has occurred from the base of the evaporite sequence, with access for the dissolving fluids provided by the Winnipegosis aquifer. However, in another area of partial solution, the potash-bearing zone at the top of the Prairie Evaporite is missing, suggesting possible solution from the top of the evaporite sequence by fluids associated with the overlying Dawson Bay strata. This latter mechanism appears less likely, however, in view of the relatively impermeable nature of the lower Dawson Bay strata. The local absence of the potash beds could possibly be explained as a "salt horse", a local facies feature unrelated to salt collapse.

Occurrences of localized salt solution above thick Winnipegosis reefs or mounds have been noted (Bishop, 1953). The Winnipegosis carbonate mounds constituted structurally high aquifers below the Prairie Evaporite, and solution may have taken place along fractures in the salt that formed as a result of differential compaction over the mounds (Holter, 1969).

In some areas of Saskatchewan, formation waters may have been deflected over positive basement relief features so as to migrate vertically along associated fractures in the overlying strata, giving rise to solution of the Prairie Evaporite and related collapse of younger deposits (Wilson et al., 1963). In Manitoba, however, there is no direct evidence of any associated basement highs, although deep well control is admittedly sparse.

**4.5 Summary**

Although the structural anomalies noted above generally must be considered as potentially unfavourable for subsurface disposal, the entire stratigraphic sequence must be examined to determine the extent of the structural deformation. If, for example, a structure is entirely pre-Mesozoic in age, the overlying Mesozoic strata may form a competent cap rock. Also, post-deformational anhydrite and dolomite emplacement, as discussed later, may have effectively sealed any structural breaks at the pre-Mesozoic unconformity surface, leaving conditions suitable for waste disposal despite the structural disturbance of the reservoir strata. Oil production from areas of Mississippian strata affected by local salt collapse is a case in point.

In contrast to the generally detrimental effects of most of the smaller-scale structures noted above, regional structural movements apparently have given rise to conditions in southwestern Manitoba exceptionally favourable for both waste disposal and oil accumulation. Regional studies indicate that pre-Mesozoic differential uplift of Mississippian strata has occurred (McCabe, 1971), exposing at the Mississippian erosion surface the basin margin facies of Mississippian reservoir beds that comprise the excellent stratigraphic traps from which most Manitoba oil production had been derived. These Mississippian traps subsequently will be shown to offer the best potential for subsurface waste disposal in southern Manitoba.

## 5.0 DETAILED STRATIGRAPHY

### 5.1 General Statement

Anomalous structural features such as those discussed above are critical in determining the disposal potential for any specific site, but a knowledge of the regional stratigraphic framework and the associated hydrodynamic flow regime are essential to determination of the disposal potential of a region or zone, which is the prime purpose of this study. As will be shown below, the basic hydrostratigraphic* subdivision utilized in this study (Fig. 5) must be modified in some areas to take into account variations in stratigraphy (especially reservoir truncation at the pre-Mesozoic unconformity) as well as major lithofacies changes in the various hydrostratigraphic units.

The following discussion relates primarily to the southwestern part of Manitoba. The Hudson Bay area will be discussed only briefly at the end of this section.

### 5.2 Basal Clastic Division (Deadwood and Winnipeg Formations)

The basal clastic division of the northern Williston Basin region is represented in most of Manitoba by up to 70 m of Middle Ordovician mudstones and sandstones of the Winnipeg Formation (Fig. 5) (McCabe, 1978). Southwest of a line extending roughly from Tp. 1, Rge. 24WPM to Tp. 8, Rge. 29WPM, in the extreme southwestern corner of the Province, the Winnipeg Formation rests unconformably on a thin wedge, up to 60 m thick, of glauconitic sandstones and micaceous shales of the Middle to Upper Cambrian Deadwood Formation (Fig. 9). Throughout the remainder of Manitoba the Ordovician clastics rest unconformably on weathered Precambrian basement.

The depositional (isopach and lithofacies) trends in the Winnipeg Formation are approximately east-west, with a progressive but somewhat irregular northward thinning. The northern, depositional edge of the Winnipeg coincides approximately with the present northern erosional limit of Paleozoic strata. Local irregularities in thickness of the Winnipeg can be attributed almost entirely to differential compaction rather than differential subsidence (McCabe, op. cit.). The uniformity of the isopach pattern, when the effects of differential compaction are removed, indicates that the underlying Precambrian erosion surface was essentially flat. To date, there is no evidence in Manitoba (as contrasted to Saskatchewan) of any appreciable paleotopographic relief on the Precambrian surface, except for the paleotopographic high at Churchill, noted previously.

In the extreme south, the Winnipeg Formation consists of a few feet of basal medium- to coarse-grained quartzose sandstone succeeded by micaceous mudstones, overlain by interbedded mudstones, siltstones and sandstones. Farther north, concurrent with the depositional thinning, the mudstones incorporate progressively higher proportions of relatively coarse grained material, in the form of sandstone and siltstone intercalations, so that the most northerly occurrences of the formation consist almost entirely of sandstones with only a few thin interbedded shales. The sandstones are typically pure, clean, poorly cemented, and show excellent porosity and permeability.

The degree of reservoir separation between the basal clastic unit and the overlying carbonate-evaporite unit is somewhat variable. For the southernmost portion of the area, where the upper beds of the Winnipeg Formation consist of impermeable shales, and the lower portion of the Red River is a dense tight dolomitic limestone, reservoir separation should be good. Tests by R. Betcher (pers. comm.) at the Dorsey disposal site (section 6.3.4.) appear to confirm a high degree of reservoir separation. In northern areas, however, where the Winnipeg Formation changes almost completely to porous sandstone and is in direct contact with overlying Red River carbonates, the degree of reservoir separation is much less.

### 5.3 Carbonate-Evaporite Division

The carbonate-evaporite division (Middle Ordovician to Silurian; Middle Devonian to Mississippian) (Fig. 5) conformably overlies the basal clastic sequence in southern Manitoba, and onlaps the Precambrian basement at the northern limit of occurrence. The carbonate-evaporite sequence is overlain with marked angular unconformity by Jurassic and Cretaceous sandstones and shales of the upper clastic division. The rate of regional truncation of the carbonate-evaporite sequence is approximately 3-4 m/km.

The carbonate-evaporite sequence has a maximum thickness of more than 1200 m in the southwest and wedges out to the north and east. The minimum thickness beneath the cover of Mesozoic deposits, along the Mesozoic erosional edge, ranges from 0 to 470 m (Fig. 10). The rocks reflect sedimentation in a variety of marine depositional environments. A major unconformity between the Silurian and Devonian Systems represents a hiatus, from latest Silurian to early Middle Devonian time. Erosion of up to several hundred feet of Silurian strata occurred during this time, with subsequent deposition of a thin sequence of red beds and local occurrences of anhydrite. Several other local and intrabasinal hiatuses are recorded in the carbonate-evaporite division, especially in the Devonian succession, where they are likewise marked by evaporites and argillaceous red beds, but with little or no associated erosion. Vertical hydraulic continuity of the Paleozoic carbonates is thus interrupted by marker beds with relatively high argillaceous content and by generally thin evaporite beds, mainly of anhydrite, but with halite becoming important in Middle and Upper Devonian units. These aquitards or aquicludes generally become thicker and more effective in the deeper parts of the basin. The most important evaporite deposit, the Middle Devonian Prairie Evaporite, consists of anhydrite, halite, sylvite and carnallite, and attains a maximum thickness of 130 m in the vicinity of the Saskatchewan border (Fig. 10). This evaporite sequence is exploited commercially in Saskatchewan for its potash minerals and halite, but as yet is not mined in Manitoba, although potentially economic deposits have been delineated and are currently being evaluated.

Although the total carbonate-evaporite division can be considered as a single hydrogeologic unit for the purposes of this study, the presence of relatively impermeable shale and evaporite interbeds, especially to the southwest, can give rise to a number of partially separated reservoir subzones, corresponding more or less with the defined formations. Figure 11 shows variations in salinity of formation brines for selected formations within the carbonate-evaporite division. Differences in salinity between the different formations reflect to some degree the extent of reservoir separation within the carbonate-evaporite division. Drill stem test data (Petroleum Branch — open file) indicate good porosity and permeability in numerous zones within the carbonate-evaporite succession.

In general, the highest salinities occur in the southwestern corner of the Province, with concentrations showing a progressive but irregular decrease updip, to the northeast. This decrease is much less pronounced in strata of the upper part of the carbonate-evaporite unit which do not extend to outcrop but are buried beneath Mesozoic shales and evaporites of the upper clastic division (Fig. 6). These upper Paleozoic strata are *completely isolated stratigraphically* from the surface and biosphere; the extent of their hydrologic isolation will be discussed later.

In view of the above data, the carbonate-evaporite division must be subdivided, for the purposes of this study, into two hydrologically

*hydrostratigraphic unit: a body of rock having considerable lateral extent and comprising a geologic framework for a reasonably distinct hydrologic system.
hydrogeology = geohydrology = groundwater geology
hydrology: study of all waters, underground, surface and atmospheric.
From: Glossary of Geology, A.G.I. (1972).

distinct regions. The first is the southwestern region corresponding geographically to the Southwestern Upland, where the truncated carbonates are overlain unconformably (capped) by a thick sequence of largely impermeable Mesozoic beds. The second is the entire region northeast of the limit of effective Mesozoic cover, which area corresponds geographically to the Manitoba Lowland, where carbonate strata extend to the bedrock surface.

#### 5.3.1 Northeastern region (Manitoba Lowland)

Carbonates of Middle Ordovician to Upper Devonian age occur at surface or beneath a generally thin mantle of unconsolidated surficial deposits over an area of about 125 000 $km^2$ of south-central Manitoba (Fig. 4). These strata constitute the most extensive and important fresh water aquifer in Manitoba, known as the "Carbonate Aquifer" (Render, 1970; Saskatchewan-Nelson Basin Board, 1972a, 1972b). The Carbonate Aquifer is an example of a hydrostratigraphic unit (Maxey, 1964) with little correspondence between aquifer boundaries and lithostratigraphic (formational) boundaries, since the most active zone in terms of groundwater movement and storage is the upper 30 m of the aquifer. The shale and evaporite aquitards, noted previously for the subsurface, are either missing or have limited effect in the near-surface environment, due primarily to near-surface fracturing and associated groundwater solution. At depth, however, particularly near the southwestern limit of this region, the aquitards are at least partially effective, and probably restrict vertical, cross-formational flow, although not sufficiently so as to delimit discrete, isolated reservoirs. All carbonate strata in this Northeastern Region (Manitoba Lowland) are thus considered to be hydraulically connected in some degree with the groundwater regime of the near-surface Carbonate Aquifer.

The dissolved solids content of the groundwater in the near-surface aquifer is generally 300-600 ppm, but increases to 10 500 ppm near the western boundary of the aquifer, near the limit of Mesozoic cover.

#### 5.3.2 Southwestern region (Southwestern Upland)

This region comprises the Southwestern Upland, and its northeastern limit is placed at the position of the Manitoba Escarpment, the limit of *effective* thickness of Mesozoic cover. A fairly wide belt of Jurassic or Lower Cretaceous strata extends for some distance beyond the Escarpment, but these strata are not sufficiently thick to provide an effective caprock. This latter area has been included as a sub-area of the Northeastern Region for hydrological purposes.

The Southwestern Region comprises that portion of the carbonate-evaporite sequence occurring beneath a Mesozoic cover, up to 1100 m thick, consisting dominantly of impermeable shales. The shale and evaporite aquitards that interrupt the Paleozoic carbonate sequence become thicker and more effective in defining a series of more-or-less discrete sub-reservoirs within the carbonate-evaporite division. The most prominent and effective aquitards are, in ascending stratigraphic order: the shaly Gunn Member of the Stony Mountain Formation (southern area only); the Ashern Formation (shale); the Prairie Evaporite/Second Red Bed interval (particularly in the salt-bearing area); the Bakken-Lyleton shale interval; and the Charles-Mission Canyon evaporites (Fig. 5, 6). In addition, in some areas, a secondary zone of dolomitization-anhydritization occurs at the Paleozoic erosion surface, where Paleozoic strata are overlain unconformably by evaporitic strata of the Jurassic Amaranth Formation; this secondary zone, where well developed, forms a highly effective caprock or seal at the unconformity surface. The effectiveness of this secondary caprock zone is evidenced by the fact that almost all Mississippian oil accumulations in southwestern Manitoba are trapped below this zone of secondary alteration (see Cross-Section, Fig. 6).*

From the above it can be seen that, hydrologically, the carbonate-evaporite division of the Southwestern Region is much more complex than in the Northeastern Region, and offers a thick sedimentary sequence with numerous sub-reservoirs showing differing degrees of separation, depending on local development of impermeable aquitards. For the purposes of regional hydrologic evaluation, however, one prime distinction must be made. The upper Paleozoic strata, from Devonian Duperow to Mississippian, are all completely truncated at the pre-Mesozoic erosion surface. Nowhere in southwestern Manitoba do these beds extend to surface; they are completely *isolated, stratigraphically and structurally* from the biosphere. In contrast, all of the underlying lower Paleozoic carbonates, although deeply buried in the Southwestern Region, extend to bedrock surface in the Northeastern Region and hence are potentially linked hydrologically to the biosphere.

For the purposes of subsurface-disposal evaluation, the carbonate-evaporite division of the Southwestern Region is therefore subdivided hydrogeologically into an Upper Zone and Lower Zone, as outlined above and as shown in Figure 6.

### 5.4 Upper Clastic Division — Mesozoic and Cenozoic Strata — Southwestern Upland

The upper clastic division in southwestern Manitoba consists of Triassic(?)-Jurassic, Cretaceous, Tertiary and Quaternary, largely detrital deposits, which rest with angular unconformity on the underlying carbonate-evaporite sequence (Fig. 6). The upper clastic sequence attains a maximum thickness of about 1100 m in the southwestern corner of the province (Fig. 12).

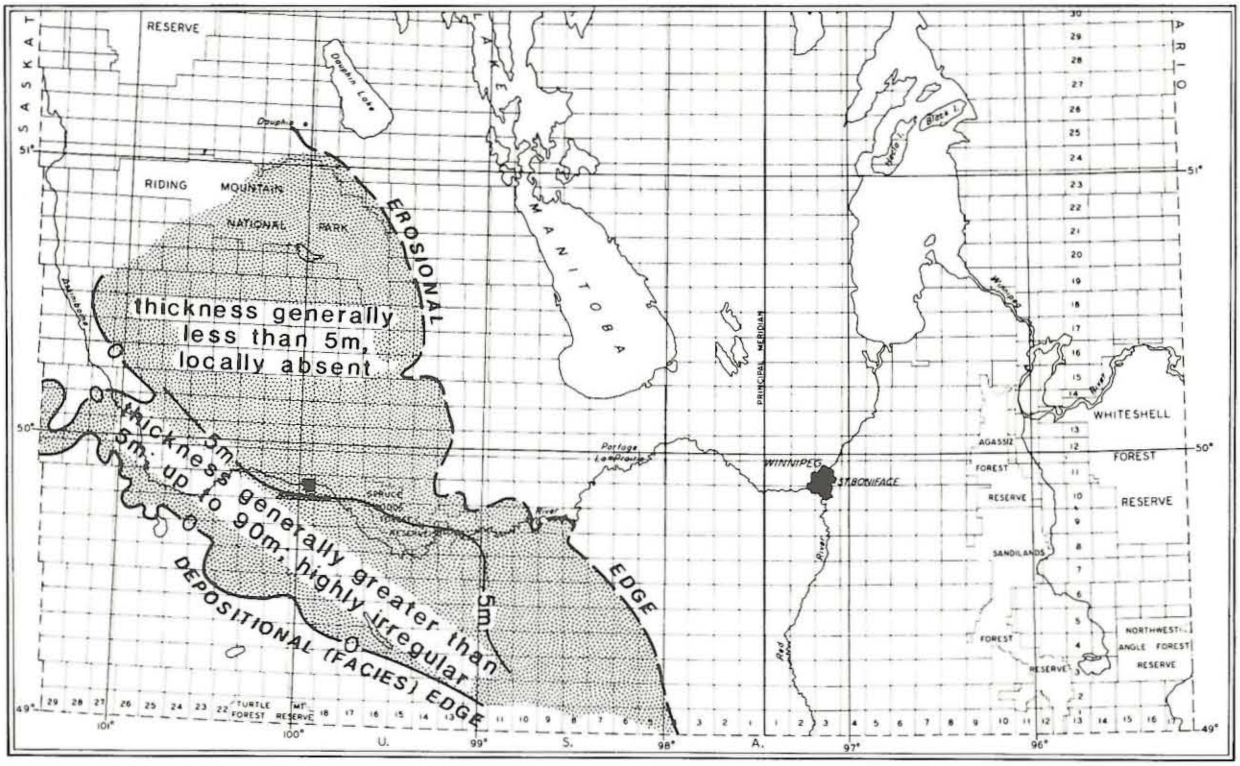
#### 5.4.1 Mesozoic strata

The basal deposits of the upper clastic division are the Triassic(?)-Jurassic red beds of the Lower Amaranth Formation, consisting of shale, silty shale and silty sandstones, succeeded by a sequence of anhydrite, dolomite and dolomitic limestone that includes the Upper Amaranth and Reston Formations. The anhydrite has been largely converted to gypsum near the outcrop belt. These strata are overlain by interbedded fine grained sandstones and shale, which are overlain by variegated shales, fine grained sandstones, calcareous sandstones and minor limestone — the Melita and Waskada Formations of Jurassic age.

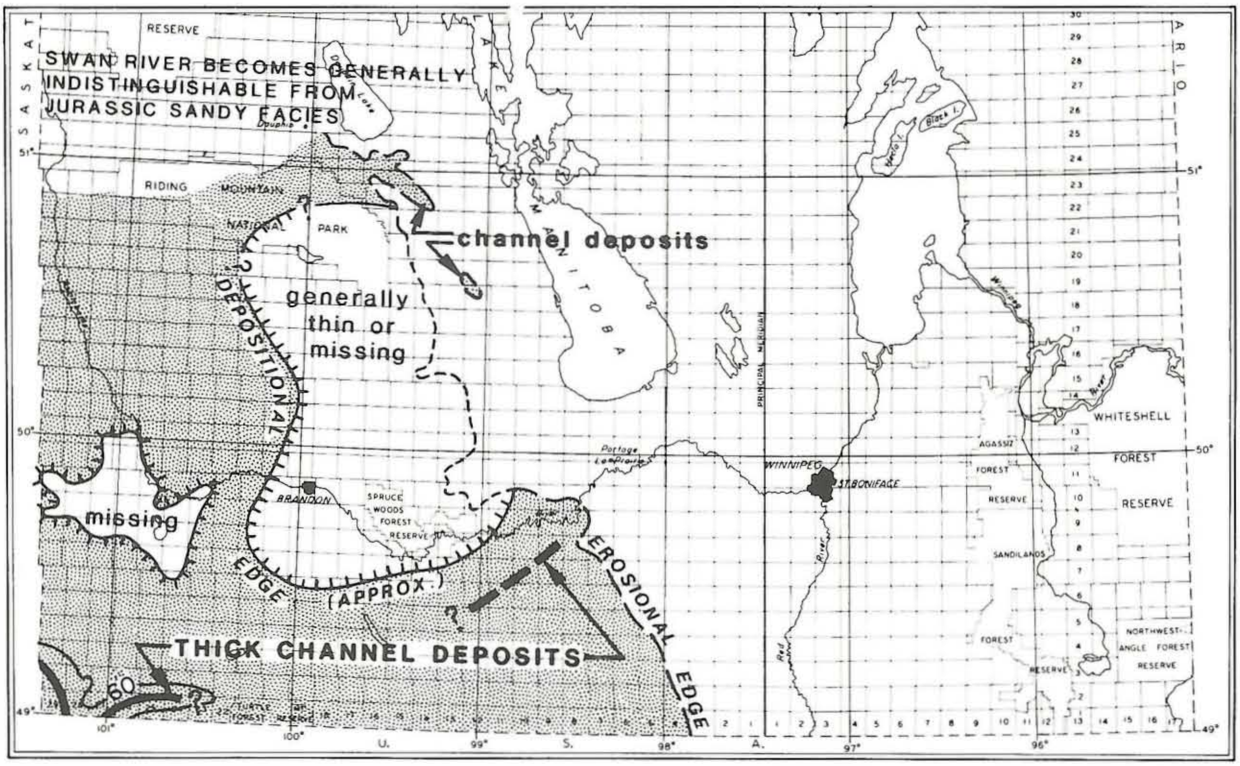
Lacustrine-fluviatile, fluviomarine and marine sandstones and shales and interbedded lignite form a basal Cretaceous sequence (Swan River or Mannville Group), which rests unconformably upon Jurassic or, locally, earlier strata. The sandstone intervals generally show excellent porosity and permeability. A number of Cretaceous outliers consist of Swan River clastics that occupy sharply defined channels deeply incised into older strata (Bannatyne, 1971; McCabe, 1971). The maximum thickness attained by the Swan River succession in Manitoba is about 120 m in a deeply incised channel south of Pierson (Fig. 13).

Swan River strata are overlain by a sequence of Cretaceous beds, dominantly marine shales, which attain a maximum thickness in the order of 820 m, and are referred to, in ascending sequence, as the Ashville, Favel, Vermilion River and Riding Mountain Formations (Fig. 5). Strata of good reservoir quality in this succession are restricted to the Ashville Sand (correlative with the Viking Sand of Saskatchewan), which occurs in the lower part of the Ashville Formation (Fig. 13). To the northeast, in the vicinity of the outcrop belt, the Ashville Sand occurs as a thin, well sorted blanket sand, commonly less than 3 m thick. To the southwest, however, on a line trending roughly southeast through Virden, and parallel to the Cretaceous depositional (isopach) trend, the sand thickens abruptly and irregularly to a maximum of about 36 m. Southwest of this line the Ashville Sand pinches out and is replaced laterally

*Recent oil exploration and development have shown that the "seal" at the Paleozoic erosion surface is imperfect in some areas. Oil discoveries in the lower portion of the Amaranth Red Beds (basal portion of the upper clastic unit), in the Waskada and Pierson areas, show that some leakage can occur from the carbonate-evaporite unit (Mississippian) into the overlying upper clastic unit. The Red Bed oil accumulation represents oil leaked from Mississippian reservoir beds, but the extent of this leakage probably is limited to the sandy permeable zone comprising the lower portion of the Red Bed sequence.




CRETACEOUS - ASHVILLE SAND (ASHVILLE FORMATION) Km 25 0 25 50 75 100 Km




CRETACEOUS - SWAN RIVER FORMATION Km 25 0 25 50 75 100 Km

*Figure 13 Distribution of principal sand zones, upper clastic unit, southwestern Manitoba.*

by shales.

Reservoir beds also occur in a sequence of up to 45 m of sands, sandstones and interbedded kaolinitic shale that forms the uppermost Cretaceous Boissevain Formation, which is exposed in flat-lying beds around the perimeter of Turtle Mountain in southwestern Manitoba.

### 5.4.2 Cenozoic strata

Tertiary deposition in the area is evidenced by at least 145 m of poorly consolidated bentonitic and carbonaceous sand, silt and clay, with minor interbedded lignite concentrated at the base, and limonitic(?) concretionary layers, all referable to the Turtle Mountain Formation (Bannatyne, 1970; Bamburak, 1971). This unit is restricted to the Turtle Mountain area which rises to an elevation of 760 m, some 240 m above the surrounding plains of the Southwestern Upland. This feature is regarded as a geologic and topographic outlier of the Missouri Coteau of Saskatchewan and North Dakota.

### 5.4.3 Quaternary

Quaternary deposits in southern Manitoba are highly variable in thickness, averaging about 30 to 60 m, but locally attaining a maximum thickness of the order of 300 m in the area of Duck Mountain (Klassen, 1971). These unconsolidated sediments consist mainly of Pleistocene till and clay, which underlie, incorporate and overlie extensive though subordinate deposits of glaciofluvial and lacustrine sand and gravel. The most extensive sand and gravel aquifers in the Province are the delta deposits of the ancestral Assiniboine River, where it emptied into glacial Lake Agassiz. These beds occupy an area of 2000 $km^2$ to the east of Brandon and have an average saturated thickness of 15 m (maximum value of 30 m).

A number of smaller, less well defined, "secondary" surficial aquifers also have been recognized in southern Manitoba (Saskatchewan-Nelson Basin Board, 1972a, 1972b; Water Resources Branch, various reports). For the most part, these are sand and gravel deposits for which single-point yields of potable water could exceed 0.03 $m^3/s$. The two largest of these aquifers are located over a 1300 $km^2$ area of the Agassiz and Sandilands Provincial Forest areas in the southeastern corner of the Province, and over an 800 $km^2$ area of the Glacial Lake Souris basin region west of the Souris River between Melita and Oak Lake. In addition, more than 15 large sand and gravel aquifers are interbedded with till, located in buried bedrock valleys, or coincident with major, modern river valleys.

## 5.5 Major Unconformities

A brief discussion of the major unconformities in the stratigraphic succession in Manitoba is presented below, because such features can have significant effects on the regional and local cross-formational flow of subsurface fluids.

### 5.5.1 Sub-Mesozoic unconformity

The most important unconformity in southwestern Manitoba, relative to regional hydrogeology, and particularly with respect to its effect on the regional subsurface fluid flow regime, is the sub-Mesozoic unconformity surface. In southern Manitoba, this erosion surface represents a karstic-trellis topography developed on the sequence of truncated Paleozoic carbonates which range in age from Mississippian in the southwest through Ordovician to the northeast (Fig. 14). Local cavernous porosity development (incipient karsting?) is reported from near-surface carbonates of the Souris River Formation west of Lake Manitoba, an area close to the limit of Mesozoic cover (McCabe, 1971). Numerous large solution channels in the Souris River Formation, up to 3 m by 10 m in cross-section and of undetermined length, have been uncovered in quarries near Mafeking (McCabe, op. cit.; Bannatyne, 1975). The latter channels are filled with fine quartzose sand and clay, probably of Cretaceous age. Conical solution caverns containing green, orange and brown clays (post-Devonian to Early Cretaceous) have been recorded from the Elm Point Formation at Steep Rock (Bannatyne, op. cit.). Features such as these, and possibly the solution-enlarged joint fissures noted by Render (1970) in the Paleozoic Carbonate Aquifer of the Winnipeg district, appear to be typical of Paleozoic rocks near the erosion surface. Such widespread solution effects near the unconformity will greatly enhance the permeability of the deposits.

In contrast, where evaporites and red beds of the Jurassic Amaranth Formation rest on Upper Paleozoic, and in particular Mississippian carbonates in southwestern Manitoba, permeability has been affected in a manner completely opposite to that outlined above. In much of this area the uppermost Mississippian rocks have undergone extensive dolomitization and anhydritization to depths of up to 30 m or more beneath the sub-Mesozoic unconformity. Dolomitization and anhydrite infilling and replacement apparently resulted largely from downward percolation of hypersaline brines during Upper Amaranth anhydrite deposition, so that the dolomitized Mississippian strata attain greatest thicknesses where the Jurassic red beds are relatively thin or totally absent, and Upper Amaranth evaporites rest directly on the Paleozoic carbonates (McCabe, 1959; Young and Greggs, 1975).

The tight, strongly indurated rocks beneath the unconformity commonly form capping lithologies for the Mississippian crude-oil reservoirs of southwestern Manitoba*, and should provide an equally effective cap for waste containment.

McCabe (1971) lists several, relatively large-scale paleotopographic anomalies on the sub-Mesozoic erosion surface (Fig. 14).

(1) Cuestas, scarps and re-entrants along the Mississippian subcrop belt have resulted from recessive weathering of shales and micritic carbonates, most notably along the Lodgepole edge and along the Virden-Whitewater Lake subcrop. Maximum relief on the Lodgepole scarp is about 90 m.

(2) An east-trending channel south of Winnipeg has relief in excess of 150 m and is filled with Jurassic red beds and evaporites which, near the eastern limit of the channel, overlap onto basement rocks of the Precambrian Shield.

(3) Beyond the present regional limit of Mesozoic strata, the sub-Mesozoic surface apparently was dissected by narrow, deep, sharply defined pre-Jurassic and/or pre-Cretaceous channels, which have given rise to numerous small outliers of Mesozoic channel fill such as the channel reported at Arborg (Bannatyne, 1970).

(4) Local closed paleotopographic highs occur in the Duperow subcrop belt south of Riding Mountain National Park (relief 60 m) and in the Dawson Bay subcrop belt at Portage la Prairie (relief 45 m).

(5) Structural and paleotopographic anomalies north of Riding Mountain National Park probably result from salt-solution and collapse accompanied by local draping over buried Winnipegosis reefs.

All of the aforementioned features can have an effect on the waste disposal potential for a given area.

### 5.5.2 Sub-Cretaceous unconformity

A major unconformity also exists at the base of the Cretaceous section. The Swan River (Blairmore/Mannville) sands show a highly variable isopach pattern reflecting deposition on a deeply eroded Jurassic surface. In the southwestern corner of the Province, thick channel-fill deposits, including basal gravels, are cut as much as 100 m into Jurassic strata. Regionally, a northward and northeastward truncation of Jurassic strata also is evident, and locally, beyond the main Mesozoic outcrop belt, Cretaceous channel-fill deposits rest directly on lower Paleozoic strata, indicating that pre-Cretaceous erosion has locally cut through the entire Jurassic section.

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*Refer to footnote, section 5.3.2.

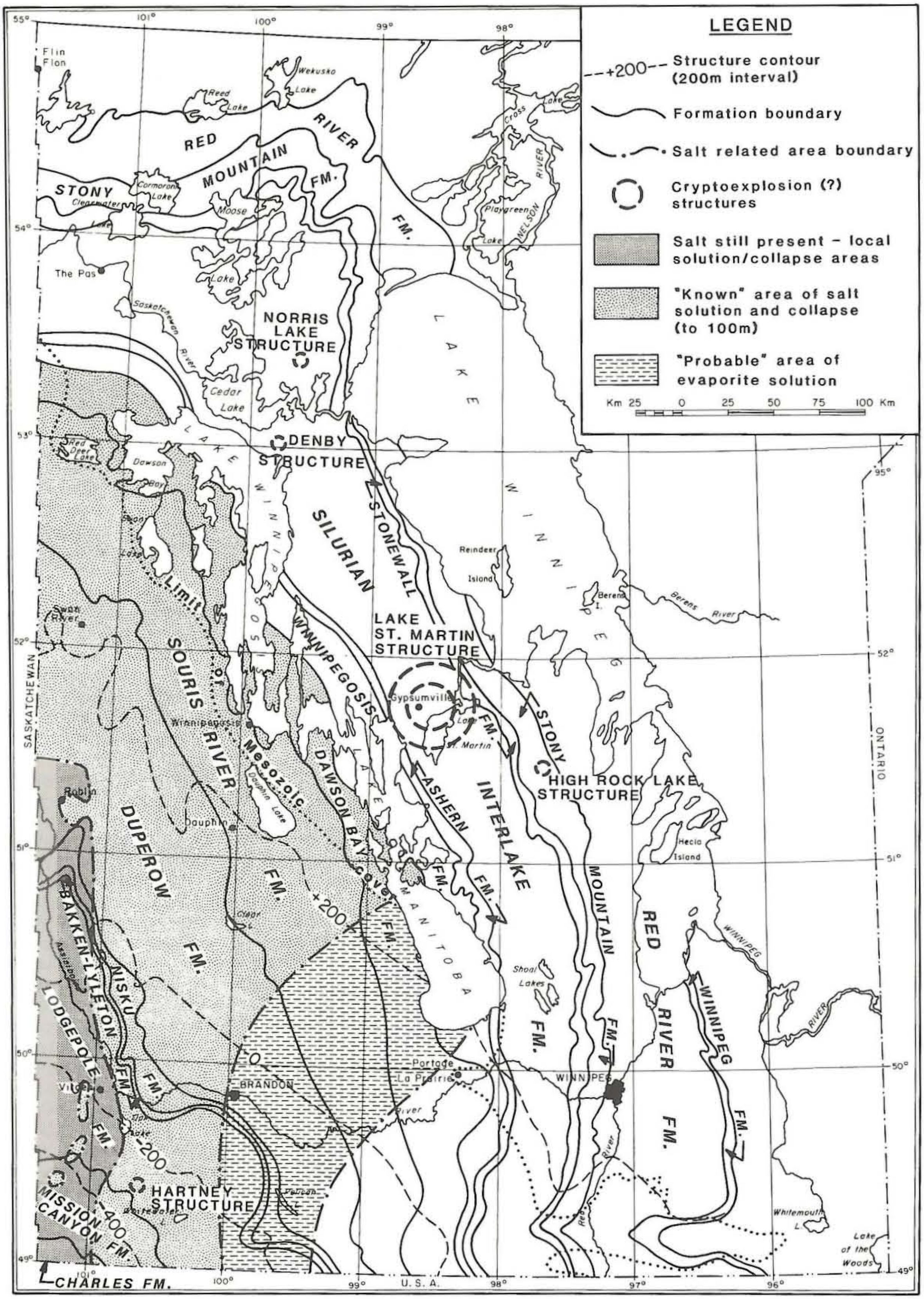



*Figure 14 Structure contour-subcrop map, sub-Mesozoic unconformity, showing areas affected by salt collapse.*

#### 5.5.3 Sub-Quaternary unconformity

The bedrock topography (pre-Pleistocene/Recent erosion surface) in southern Manitoba (Klassen et al., 1970; Klassen, 1971) is reflected in the elements of surface relief. On a regional scale, bedrock relief and surface relief are approximately the same, except on the Duck Mountain and possibly Porcupine Mountain uplands, where the relief of the bedrock is much less than that of the surface. Bedrock depressions beneath the Assiniboine delta and Valley River plain are the sites of major pre-glacial drainage channels.

### 5.6 Hudson Bay Region

In the Manitoba onshore portion of the Hudson Bay Basin region, the Paleozoic carbonate-evaporite sequence can be subdivided into three hydrogeologic units (Fig. 5):

(1) a lower, Middle Ordovician through Middle Silurian sequence consisting of a thin basal sandstone succeeded by limestones with minor interbedded dolomite, evaporites, and locally in the Attawapiskat Formation, porous biohermal deposits.

(2) a medial, Upper Silurian, dominantly clastic and largely impermeable sequence of fine grained siltstones, shales and red beds with subordinate evaporites; and

(3) an upper, Lower to Middle Devonian sequence consisting of dense to fossiliferous limestones with minor dolomite, silty argillaceous dolomite, anhydrite and chert.

In Manitoba, no Mesozoic deposits are known to overlie the Paleozoic sequence in the Hudson Bay Basin area, but almost the entire onshore portion of the basin is mantled by a thick cover of Pleistocene deposits ranging from 45 to 120 m in thickness and probably averaging about 60 m (on the basis of limited drillhole data). Exposures of bedrock are limited almost entirely to occurrences along deeply incised river channels, in particular the Nelson and Churchill Rivers. Surprisingly, the thinnest known drift cover, aside from anomalous exposures in the Churchill area (associated with a major Precambrian paleotopographic high), is at the mouth of Kaskattama River, where an oil well test hole intersected only 7 m of overburden on top of Devonian limestones.

Because drilling in the area is at an early reconnaissance level, little is known about either lithofacies variations within the various stratigraphic units, or variation in composition of formation waters. No major unconformities are known, hence no stratigraphically isolated (truncated) aquifers can be defined, such as those noted previously in southwestern Manitoba at the pre-Mesozoic unconformity. Local facies traps may occur where Silurian Attawapiskat reefs are enclosed in the argillaceous strata of the overlying Kenogami River Formation.

# 6.0 SUBSURFACE DISPOSAL OF WASTE IN MANITOBA — CURRENT AND POTENTIAL REQUIREMENTS

### 6.1 General Statement

A review of current types of waste disposal, and also possible future requirements for waste disposal is in order, prior to a discussion of the detailed hydrogeologic potential for future subsurface waste disposal in Manitoba. However, before discussing Manitoba's specific waste disposal requirements, it is necessary to present a brief outline of the various types of liquid industrial waste.

### 6.2 Classification of Liquid Industrial Waste

Although a detailed discussion of the classification of liquid industrial waste is highly complex and beyond the scope or requirements of this report, a brief review is desirable since degree of toxicity of the waste determines the degree of subsurface containment necessary for "safe" disposal. Quantitative evaluation of both degree of long-term waste toxicity in the subsurface environment and degree of long-term waste containment are not possible, however, with the presently available data.

Van Everdingen and Freeze (1971) have subdivided liquid industrial waste into two categories — "natural" and "foreign"

> "Natural wastes contain in solution only constituents that are found normally in solution in the subsurface. The concentrations of the various constituents, however, may differ from those usually associated with a particular disposal formation".

Since many toxic substances can occur naturally in trace amounts in normal surface and subsurface waters (e.g., mercury, arsenic) some further limitation should be specified. Possibly, concentrations in "natural waste" should not exceed maximum concentrations found in natural formation waters. Natural wastes would thus include: saline brines produced by the petroleum industry; waste brines generated by the potash and salt industries; waste brines generated during solution of salt beds for natural gas storage caverns, etc. A recently proposed project for subsurface disposal of backwash fluids from a large water-softening system involves a waste fluid that is essentially a "natural" waste. Natural wastes pose no major toxic hazards for subsurface disposal, although extensive leakage into freshwater reservoirs would cause serious, but not dangerous, problems.

All other (non-natural) liquid industrial waste is classified by van Everdingen and Freeze as "foreign", with two principal subtypes: radioactive wastes, and other liquid industrial wastes. Most "foreign" wastes are toxic to some degree so that any leakage from the disposal zone back into the biosphere will have serious, if not disastrous, environmental effects, as for example the leakage of dioxin and other toxic chemicals from the Love Canal into the Great Lakes system.

For subsurface disposal purposes three principal factors must be considered in classification or evaluation of "foreign" wastes: toxicity, reactivity or stability, and volume/rate of disposal.

Acceptable or maximum allowable levels of concentration for most chemical and radioactive "foreign" contaminants have been established under the Public Health Standards Act. A relative measure of waste toxicity could be based on the ratio of waste concentration to the maximum acceptable concentration.

Reactivity or stability of waste in the subsurface environment is equally as important as waste toxicity. As noted by van Everdingen and Freeze (op. cit.):

> "Essentially nothing is known about the behaviour of many of these (foreign) wastes when they come into contact with natural formation fluids and rocks, under the conditions of elevated temperature and pressure that prevail in the subsurface. Toxicity of some constituents may either increase or decrease through degradation; chemical reactions between relatively harmless compounds may produce more toxic compounds".

In general, however, most physical/chemical waste reactions in the subsurface probably lead to a decrease in toxicity, in many cases by absorption and by the formation of relatively insoluble precipitates that may become more or less fixed or immobilized in the subsurface environment. McLean (1968) notes four types of chemical reaction that can lead to precipitate formation:

1. Alkaline earth precipitates (insoluble carbonates, sulphates, phosphates and fluorides of calcium, strontium and barium).
2. Heavy metal precipitates (insoluble carbonates, bi-carbonates and sulphides of iron, chromium, aluminum, cadmium, zinc and manganese).
3. Oxidation-reduction precipitates.
4. Formation of organic polymers.

Unfortunately, precipitate formation, which may be favourable for subsurface waste containment, will tend to clog the reservoir beds, limiting their disposal capacity. *In situ* reservoir treatment (e.g., acidization) can in some instances be used to remobilize precipitated waste, clean the reservoir, and then permit reprecipitation of the waste farther from the drill site (e.g., the Maples refinery waste disposal project, Part II of this report). Here again, detailed studies of specific waste reactions with reservoir rocks, formation fluids, and reservoir treatment fluids must be undertaken to evaluate the overall potential for waste disposal. McLean (op. cit.) also notes that plugging of reservoirs can occur through the growth of anaerobic bacteria in the waste fluid.

The final factor to consider in a general classification or categorization of liquid wastes is the required volume and rate of waste disposal. The capacity of any subsurface reservoir to accept large volumes of liquid waste is limited, even when the waste is entirely compatible with the reservoir. For totally isolated reservoirs, additional fluid can be accepted only by means of compression of existing reservoir fluid, which will result in pressure build-up and eventual rupture of the reservoir strata once the injection pressure exceeds the overburden pressure and the cohesive strength of the rock. Escape of wastes to lower pressure, nearer surface conditions can then occur. In the case of a stratigraphically open reservoir, which somewhere extends to surface, much larger volumes of waste can be accepted, provided that reservoir permeability is sufficient to permit fluid migration without excessive pressure build-up in the reservoir. As will be shown later, many reservoir strata in Manitoba have very large capacities, although the *rate* at which waste could be injected without exceeding overburden pressure and fracturing the reservoir may, in some cases, be relatively low because of low permeability. Any precipitate formation due to waste reaction with the reservoir can greatly reduce reservoir capacity, although pretreatment of waste and use of fluid buffers can greatly reduce such precipitate formation. In general the lower the injection rate, the smaller the volume of waste to be disposed of, and the more compatible the waste with the reservoir — the wider will be the choice of potential disposal zones.

### 6.3 Liquid Industrial Wastes in Manitoba

To date, subsurface disposal of industrial wastes in Manitoba has entailed confinement and containment of both liquid and solid substances, representing only a limited range of waste categories. "Natural" wastes include brines associated with crude oil production and injected back into deep strata in the oilfield district in salt-water disposal and pressure-maintenance operations. The waste brine from the Dorsey converter station would also be classed as a "natural" waste. The only "foreign" wastes disposed of to date consist of spent caustic from a refinery, injected into Mississippian reservoirs at the Maples oilfield (Simpson, 1978a).

Deep-well disposal of wastes is frequently characterized by considerable uncertainty (Dennison and Simpson, 1973; Simpson and Dennison, 1975), because of poor well control with respect to the target aquifer in the vicinity of the disposal site.

Subsurface-disposal operations in Manitoba are noteworthy in that the uncertainty inherent in underground waste management has been considerably reduced, because of the existence of numerous wells drilled to the disposal strata:

1. Injection of oilfield brines back into producing Mississippian strata, as part of pressure-maintenance and salt-water-disposal operations, is carried out in areas where lithologic variation and flow characteristics of the brine-receiving (and oil-producing) reservoir are well known from numerous, closely spaced wells (McCabe, 1963).
2. Refinery-waste disposal into Mississippian carbonates at the Maples oil field was likewise supported by a relatively high level of subsurface information, available for nearby oil-producing wells (see Part II, this report).
3. Disposal of spent cooling water into the Paleozoic Carbonate Aquifer of metropolitan Winnipeg is also at a location of good well control with respect to the disposal (water-producing) aquifer, as demonstated by Render's (1970) detailed account of reservoir properties.
4. Prior to implementation of the Dorsey brine disposal system, data from a number of oil well test holes in the general area were evaluated, and a test hole was drilled specifically to determine if subsurface disposal was a viable option.

The distribution of subsurface-disposal systems in southern Manitoba is shown in Figure 8.

**6.3.1 Oilfield-brine injection**

The first oil discovery in the Canadian part of the Williston Basin region was made in 1951 by the California Standard Company at Daly, Manitoba where high-gravity crude oil (32° API) was found in carbonates of the Mississippian Lodgepole Formation at a depth of 762 m. Most known reserves of crude oil in Manitoba were discovered in the years 1951-1957 in Mississippian carbonates of fourteen main fields at depths of 610 to 943 m. Light to medium crude oils are produced from Lodgepole and Mission Canyon reservoirs, most importantly in the Daly and Virden districts of southwestern Manitoba. The hydrocarbons occur in structural-stratigraphic traps formed by truncation of the Mississippian oil-producing units at the sub-Mesozoic unconformity (Fig.6). The unconformity surface is overlain by impermeable Amaranth (Jurassic) red beds and evaporites which, together with secondarily dolomitized and anhydritized Mississippian carbonates immediately below the erosion surface, constitute an effective caprock.* Several different types of truncation-trap configuration are described and discussed in detail by McCabe (1959, 1963).

Brines withdrawn during commercial production of crude oil were found to contain from 5 000 to 120 000 ppm chloride, and were isolated from potable water by injection into deep, confined aquifers of Jurassic, Cretaceous and Mississippian age. Brines were transported to the disposal sites by means of pipelines of a specially constructed brine-gathering system, and by tank truck. Furthermore, some wells were completed as dual oil producers and salt-water disposal wells, discharging brine back into deeper parts of the Mississippian reservoir. Subsequently, in 1959, the California Standard Company initiated a pilot waterflood program in the central part of the Daly field, where oil wells had suffered a sharp decline in production. The secondary-recovery progam proved highly successful in stimulating production from these wells and was subsequently expanded to other parts of the field, both through drilling of additional injection wells and conversion of existing producers to water injection. The water for flooding is taken from the brine-disposal gathering system and initially was supplemented by brine from additional water supply wells completed in Cretaceous and Devonian strata. The brines undergo surface treatment prior to injection. Salt-water injection programs were subsequently initiated in other producing areas. Detailed salt-water-disposal and salt-water-injection data are issued annually by the Petroleum Branch in their Production Statistics and Activity Reports.

**6.3.2 Refinery-waste injection**

Deep-well disposal of "foreign" industrial wastes in Manitoba is represented by a single facility, operated from October, 1969 to October, 1975 by Imperial Oil Enterprises Limited for disposal of refinery wastes. A total of 8934 $m^3$ of waste was disposed of in Mississippian reservoir beds in an "abandoned" well in the Maples field. A detailed case history of the disposal program will be presented in Part II of this report (Simpson et al., in preparation).

**6.3.3 Spent cooling water**

Groundwater from the Paleozoic Carbonate Aquifer was utilized by the City of Winnipeg for water-supply purposes from 1900 to 1918, when the Greater Winnipeg Aqueduct was completed. Subsequently, wells were drilled in the central Winnipeg district to supply water for air-conditioning in theatres and restaurants, and for cold-storage plants, requiring large quantities of cold water during peak operating periods (Render, 1970). A groundwater sewage tax was introduced to encourage recharge to the Carbonate Aquifer by injection of the spent cooling water. Render (op. cit.) noted that eight recharge systems were initiated between 1940 and 1960. Return of the warmed cooling water into the aquifer has resulted in groundwater temperatures of up to 10°C at some sites within the urban area, whereas water temperature elsewhere in the southern part of the aquifer is from 4° to 6°C (Render, op. cit.).

**6.3.4 Waste brine from water softener**

From 1972 to 1985, Manitoba Hydro annually disposed of 36-45 million litres of low salinity brine and waste water, produced as backwash from the water softener system at their Dorsey D.C. converter facility, located approximately 8 km northwest of Winnipeg (Sec. 8, Tp. 12, Rge. 1E). This waste had a total dissolved solids content of only 21 000 mg/l and was discharged to the surface drainage system. The salt content of the waste had no appreciable detrimental effect on the environment, but the continuous surface flow proved to be a problem. A study by Manitoba Hydro showed that the only economically viable alternative to surface disposal was subsurface injection, and in 1984 the Water Resources Branch of the Department of Natural Resources assisted Manitoba Hydro in a detailed evaluation of the subsurface disposal potential at the Dorsey site.

A test hole was drilled to basement, and detailed hydrologic studies were made of the Winnipeg Formation sandstone aquifer to determine the nature of the formation waters and the degree of hydraulic isolation of the Winnipeg aquifer from the overlying carbonate fresh water aquifers. All tests proved acceptable and the test hole was then completed as a monitor well, while a second hole was drilled as a disposal well. Disposal requirements are for 6.8 million litres per year of waste at an injection rate not to exceed 3 l/s. Salinity of the natural formation waters in the Winnipeg Formation was determined to be 113 000 mg/l so the waste stream at 21 000 mg/l is considerably "purer" than the formation fluid.

Although no precise licensing and application procedure was followed in establishing this subsurface waste disposal system, all of the necessary technical requirements were observed and all regulatory authorities were contacted and indicated that they could not foresee any detrimental effects if the project was undertaken. Initial waste injection is planned to commence in 1986.

**6.3.5 Sewage treatment**

The newly installed sewage treatment facilities at Virden and Portage la Prairie do not really fall in the category of subsurface disposal, since the facilities merely treat the waste prior to surface disposal. The unique feature of this technologically new process is the treatment vessel, a steel cylinder up to 1.37 m in diameter and 137 m long that is emplaced in a 1.7 m diameter hole drilled to a depth of 137 m.

In the case of the Portage la Prairie facility, the shaft penetrated 55 m of Pleistocene deposits, largely till, and 82 m of Devonian and Silu-

*See footnote, section 5.3.2, re: leakage of caprock.

rian carbonates and minor shales (Dawson Bay, Winnipegosis, Ashern and Interlake Formations). Treatment of waste thus takes place in the "subsurface", but the treatment vessel will be pressure tested periodically to ensure that leakage into the subsurface does not occur. At both the Virden and Portage la Prairie facilities, no fresh water aquifers were intersected during emplacement of the reactor vessels, so the consequences of any containment failure would be minimal.

No further discussion will be presented regarding such facilities, because no subsurface dispersal of waste should occur. Nevertheless, careful monitoring of such facilities is necessary, and choice of location is important because of the potential for aquifer contamination if failure of the treatment vessel should occur. It is anticipated that such "subsurface" treatment facilities may become more common in the future because of better land utilization, higher efficiency, and avoidance of "lagoon perfume" characteristic of many surface treatment facilities.

### 6.4 Underground Waste Management in Adjacent Areas

It is noteworthy that within the Williston Basin region as a whole, deep-well injection of fluid industrial wastes is largely restricted to the broad, relatively shallow Canadian margin of the basin (Simpson and Dennison, 1975). In North Dakota, where the basin fill attains a maximum thickness in excess of 5100 m, fluid injection appears to be, for the most part, confined to salt-water-disposal and pressure-maintenance operations of the oilfield districts, although the caption of a figure, provided by Arndt (1972, Fig. 10, p. 9) is an explicit statement of contamination of a water supply by injected sewage from an unspecified "small town in western North Dakota". Oilfield-brine injection accounts for all fluid disposal down wells in neighbouring South Dakota and Montana.

In Saskatchewan, however, deep-well injection of fluid industrial wastes, exclusive of oilfield operations, has been employed as a viable mode of disposal since 1958 (Simpson and Dennison, 1975). Some 32 waste-injection operations have been initiated in the Saskatchewan area to receive large quantities of "natural" brines produced as a result of commercial solution of evaporite minerals, and comparatively minor volumes of "foreign" fluids, generated by two refineries and one chloralkali plant.

Brines, generated by seven companies in the processing and mining of potash ore from the Middle Devonian Prairie Evaporite, are injected in thirteen disposal systems. Reservoir strata at depths in the range of 441 to 1430 m receive potash-refinery brines at injection rates of 662 to 4165 l/m and pressures of 1240 to 6271 kPa. Brines are also produced through the controlled solution of evaporite strata to create artificial caverns for the underground storage of liquified petroleum gases and are injected down eleven wells into aquifers 485 to 1085 m deep at rates of 750 to 1300 l/m and pressures of 0 to 12 000 kPa. A Saskatoon chemical plant used a single well to inject herbicide wastes at 75 l/m and 1030 to 1760 kPa and mercury-contaminated brines at 75 l/m and 1200 to 1720 kPa at different times into an aquifer at a depth of 565 m; the same chemical plant utilizes three salt caverns at depths of 1020 to 1035 m and mercury compounds are permitted to accumulate in these. A salt plant near Unity disposes of waste brines down a well to a depth of 858 m at 151 l/m and 4830 kPa. Refinery wastes are injected at two facilities: the respective disposal depths are 820 and 1170 m; injection rates, 11 and 83 l/m; and injection pressures, 0 to 2400 kPa. To date, subsurface disposal has a good record of safety in Saskatchewan. However, it should be noted that nowhere in the Williston basin region is there to be found a disposal facility comparable to the Maples injection well in Manitoba, in terms of degree of detail known about the disposal reservoir and relatively hazard-free disposal strategy.

The locations of the 32 Saskatchewan waste-injection systems, noted above, are shown in Figure 15; twenty-six additional facilities are located in Alberta. All facilities of the entire northern Williston basin region are situated in the Saskatchewan-Nelson drainage basin (Fig. 15). Clearly, failure of disposal systems, and contamination of surface waters in Saskatchewan and, to a smaller extent, Alberta could have serious interprovincial consequences from the standpoint of Manitoba.

Failure of subsurface containment could also ultimately affect Manitoba, since the outcrop belts of central Manitoba are "downstream" (updip) from the Saskatchewan disposal zones relative to the previously noted basinwide groundwater flow regime.

### 6.5 Possible Future Waste-disposal Requirements

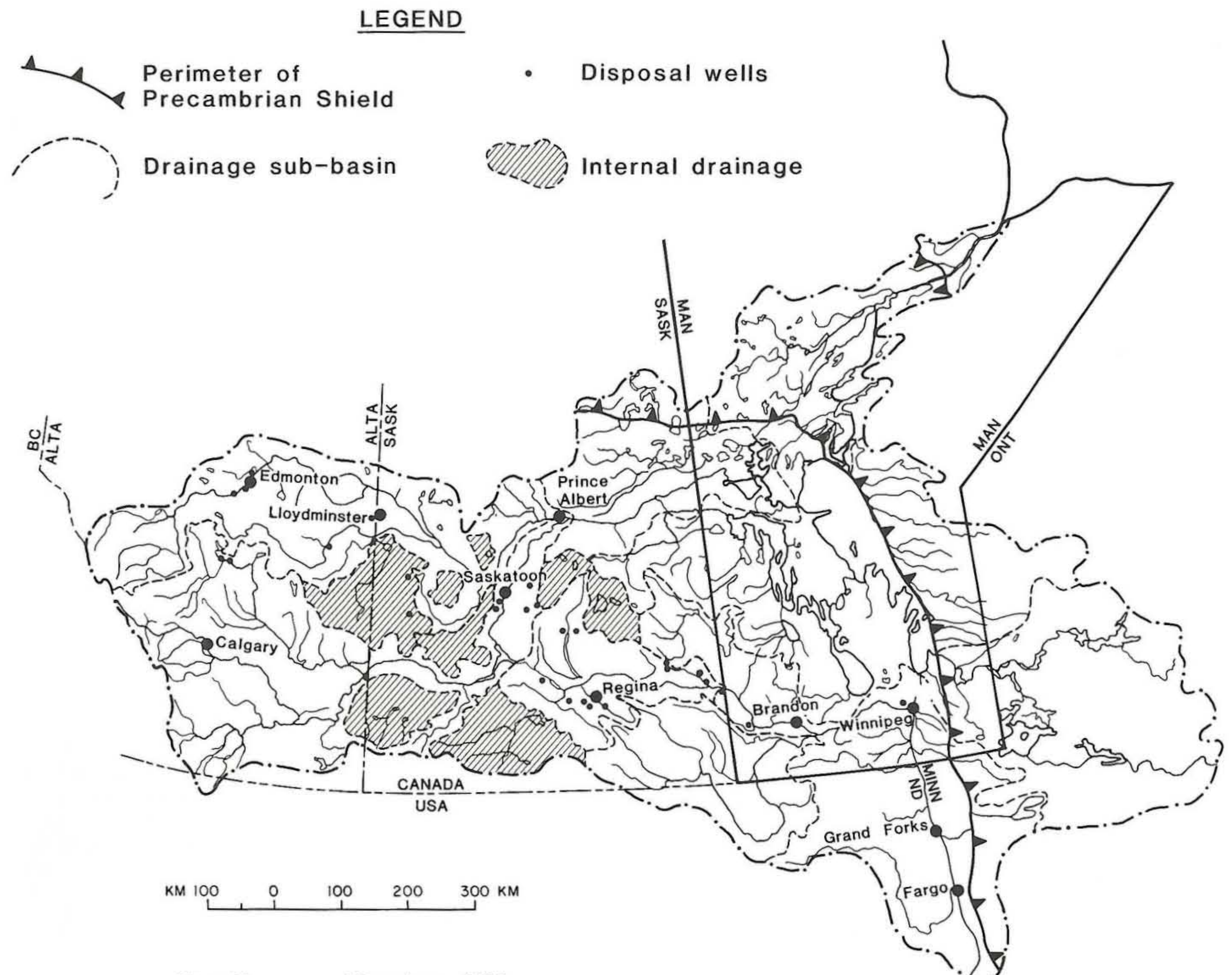
Southern Manitoba has a highly diversified industrial economy in the southeast (Winnipeg and environs), while farther west agriculture and the oil industry attain greater importance. This striking regional segregation of contrasting types of input into the province's economy has some interesting implications for the possible future of subsurface waste disposal in the area:

1. Industrial operations generating foreign waste are concentrated to a large extent in the Winnipeg district. As will be detailed later, neither surface disposal nor deep-well injection of such substances is feasible in this area because of the risk of contaminating municipal and industrial water supplies. Therefore, deep-well disposal can only be seriously considered as an option at sites distant from the waste-generating facilities. Since off-site disposal is likely to be of increasing importance in the future, the experience of waste injection at the Maples disposal site (Part II, this report) is expected to assume considerable practical value for any future disposal-well operators.
2. One of the major future sources of liquid industrial waste could be the potash mining industry. The economic potential of the Middle Devonian Prairie Evaporite for underground mining of potash in the St. Lazare district of southwestern Manitoba is thought to be good (Bannatyne, 1960, 1971, and 1983). Renewed exploration and evaluation was undertaken in 1980. The main potash-bearing unit of the Prairie Evaporite in Manitoba is 2 to 3 m thick and contains 19 to 25 per cent $K_2O$.* The unit occurs at depths as shallow as 780 m below surface and is overlain by 18 to 26 m of halite. The unit has not been exploited commercially as yet, either for production of potash or mining of common salt. Solution mining of potash in Manitoba appears unlikely because of the relatively thin sequence of potash-bearing beds in Manitoba, as compared to Saskatchewan.

A further possible means of exploiting the Prairie Evaporite might be through artificial solution of halite to create caverns for the underground storage of liquified petroleum gases.

In all instances of evaporite "mining", large volumes of waste brines would be generated. Surface impoundment of such brines in surface lagoons and ponds renders arable farmland useless and, as noted by Vonhof (1971), presents the danger of contamination of both surface waters and near-surface aquifers. For these reasons, potash-mine operations in Saskatchewan have come to adopt deep-well injection as the principal mode of disposal for waste brines. The same hydrogeologic factors that control waste injection by the Saskatchewan operations are likely to be valid in Manitoba. In Saskatchewan, potash-brine injection is on-site at high pressures (up to 6200 kPa) and high rates (up to 5 000 l/m). Disposal is into stratigraphic units located below the Prairie Evaporite so as to minimize the hazard of mine flooding (Simpson and Dennison, 1975). The disposal aquifers utilized by Sylvite of Canada Limited and International Minerals and Chemical Corporation (Canada) Limited, who operate potash mines located a short distance west of the Saskatchewan-Manitoba border, are the biostromal deposits of the Silurian Interlake Group and siliciclastic rocks of the middle Ordovician Winnipeg Formation. These same units might be exploited for emplacement of waste potash brines in Manitoba.

*More recent exploration has outlined additional, higher grade potash deposits in the Binscarth-Russell area.




After Simpson and Dennison, 1975

*Figure 15 Distribution of deep-well injection systems in the Saskatchewan-Nelson drainage basin, exclusive of salt water disposal for oil fields.*

Two additional types of subsurface waste disposal have recently been proposed for Manitoba. One is a municipal water supply system utilizing slightly saline (non-potable) formation waters, with purification by a reverse osmosis process. The waste would be a "natural" brine very similar to the Dorsey waste (section 6.3.4), and would be disposed of in a deep stratigraphic zone below the producing aquifer. This type of system is being considered for the town of Minitonas (Tp. 36, Rge. 26W), and also has the potential for use in other areas.

The second proposal, for the Brandon area, involves an estrogen-producing plant. The waste product is a nitrogen-rich "foreign" waste (objectionable but non-toxic), and the suggested disposal zone would be the basal clastic unit — the Winnipeg Formation (A. Pedersen, Water Rights Board, Department of Agriculture, pers. comm.).

## 7.0 CONSERVATION OF SUBSURFACE RESOURCES — A CONSTRAINT ON SUBSURFACE DISPOSAL

### 7.1 General Statement

One of the prime constraints on any subsurface disposal program is that valuable subsurface resources should not be endangered. Any subsurface disposal of toxic foreign waste will irretrievably "destroy" some potential subsurface resource, either formation fluid (hydrocarbon, brine, fresh water or natural gas), formation rock itself (salt, potash, limestone), or the potential of the formation for alternative use such as gas or liquid storage in natural or artificial porosity.

The following section reviews briefly the current and potential subsurface resources to be considered in southwestern Manitoba. For formation brines, a choice must be made between utilization as a disposal zone or utilization of the brine as a natural resource. A general attempt will be made, where possible, to suggest priorities for subsurface resource utilization.

### 7.2 Hydrocarbons

In no case should disposal be considered in an area of hydrocarbon accumulation. This will obviously be no problem in view of the near-absolute economic priority presently given to hydrocarbon resources. Depleted hydrocarbon reservoirs, however, can offer useful disposal sites, as will be outlined later, but caution must be exercised that the resource is in fact truly depleted. New secondary and tertiary recovery techniques, and changing economics can, and have, turned "depleted" deposits into valuable producing areas.

### 7.3. Natural Gas

Natural gas is produced in Manitoba, but only as a by-product of oil production, from gas contained in solution in the oil. No separate hydrocarbon gas accumulations are known. However, a large non-hydrocarbon (nitrogen) accumulation has been outlined in the Daly Field area. This high-purity nitrogen occurs in several different stratigraphic zones (Devonian) in a well defined structural trap. This trap could provide a potential waste disposal site, although the nitrogen itself is of possible economic use. The trap has been considered as a possible natural gas storage site, and is presently being evaluated for such a purpose. In general, traps of this type (structural) probably should be reserved for alternative resource utilization rather than used for waste disposal.

### 7.4 Potash and Rock Salt

Potash deposits of mineable grade are present in the Devonian Prairie Evaporite beds of the St. Lazare-Russell area (Fig. 10). No "foreign" waste disposal should be allowed in such areas. However, disposal of "natural" waste brines from potash processing plants will undoubtedly be required if or when potash mining is implemented.

South of the potential potash mining area, where the evaporites are too deep to permit underground mining (and the potash beds are too thin to permit potash solution mining), the lower evaporite beds could possibly be utilized as a source of high-purity NaCl brine. Hooker Chemicals considered this option prior to utilizing natural formation brine at their Brandon plant (see Section 7.6); their Prairie Evaporite salt test hole in the Roblin area unfortunately intersected a salt-solution sink. Soluble salt beds also offer the potential for storage of LPG or natural gas in artificial solution caverns.

All alternative uses listed above would have to be considered and evaluated before initiating subsurface disposal in, or in proximity to, the Prairie Evaporite salt beds. The deepest, most southerly area, farthest removed from the potential potash producing area would seem to have the best potential for waste disposal.

### 7.5 Freshwater Aquifers

Disposal of natural or foreign wastes, or leakage of any such wastes, into any portion of a freshwater aquifer must be strictly prohibited. This is the single most important constraint of any disposal project, since near surface aquifers containing fresh water are widely used for domestic, agricultural, municipal and industrial water-supply purposes and will become increasingly more valuable in the future.

The most noteworthy example is provided by the previously described Carbonate Aquifer in the metropolitan Winnipeg district, which yielded up to 0.56 $m^3$/sec. on a continuing basis through a well field supplying the City of Winnipeg from 1900 to 1919 (Render, 1970; Saskatchewan-Nelson Basin Board, 1972a). The aquifer still supplies water for individual, municipal and air-conditioning purposes in metropolitan Winnipeg at a total estimated annual pumpage of $8.8 \times 10^3$ hectare-metres (Render, op. cit.). Significant quantities of water, in the order of 0.075 hectare-metres per year, are also obtained from the same aquifer at both Selkirk and Gimli (Saskatchewan-Nelson Basin Board, op. cit.). The total discharge rate from the aquifer due to man is about $2.7 \times 10^4$ hectare-metres per year, which includes discharge into the Red River Floodway, uncontrolled discharge through flowing artesian wells, and discharge through thousands of low-capacity domestic wells, in addition to the pumpage noted above (Saskatchewan-Nelson Basin Board, op. cit.). The Carbonate Aquifer is the most extensive in southern Manitoba, but Mesozoic sandstone and fractured shale aquifers in western Manitoba, uppermost Cretaceous and Tertiary sandstones of the Turtle Mountain area, and Quaternary sand-and-gravel aquifers are also used for water-supply purposes at a wide variety of locations.

In addition to the true freshwater aquifers noted above, many (deeper) aquifers contain water that is slightly saline or brackish and hence non-potable. As noted in Section 6.3.4, recent proposals have been made to purify such brackish waters by means a of reverse osmosis process, to produce a water supply suitable for domestic use. In effect, this widens the scope of "freshwater aquifers" that should be protected as a valuable subsurface resource.

### 7.6 Salt Water Aquifers

Relatively deep, high-salinity formation brines have long been exploited for their content of dissolved solids by companies in southern Manitoba. From 1932 to 1970, at the town of Neepawa, the Canadian Salt Company Limited produced salt from subsurface brines (170,000 to 180,000 ppm) obtained from reservoir zones in the Souris River and Winnipegosis Formations, at depths of 354 m and 443 m, respectively (Fig. 8). The salt was precipitated by the vacuum-pan evaporation process and chlorides of calcium, magnesium and potassium were recovered as a by-product (Bannatyne, 1960). From 1971 to 1978 deep formation brines were also withdrawn for commercial purposes by Hooker Chemical Canada Limited east of Brandon. Brine production was obtained from the basal portion of the Red River Formation plus all of the Winnipeg Formation in one well, and the Winnipegosis Formation in a second well. The composition of the Winnipegosis brines (J.D. Ross, pers. comm. to Simpson, 1973) is shown in Table IV. Hooker's process utilizes electrolysis of brines to produce sodium chlorate, chlorine, caustic soda, sodium carbonate and muriatic acid. The two brine supply wells have now been abandoned, and Hooker is presently obtaining its salt as a by-product from a Saskatchewan potash mine.

Potential future uses of formation waters include production of calcium and magnesium from the highly saline brines of deep aquifers, such as proposed by Hitchon and Holter (1971), and the extraction of scarce halogens such as bromine and iodine, also from deep brines.

Bannatyne (1960) presents a detailed discussion of saline brine production in Manitoba, and also outlines all zones of highest salinity. Additional analytical data are listed in the Mineral Resources Division publication "Lower Paleozoic Formation Water Analyses, Bakken to Precambrian", including total salinity maps for each formation.

Inasmuch as the Winnipegosis Formation has been used as a brine supply aquifer, shows some of the highest reported salinities, and exhibits excellent porosity and permeability (M.R.D. Table of Lower Paleozoic Drill Stem Tests), consideration could be given to preserving the Winnipegosis as a brine supply aquifer, and prohibiting foreign waste disposal in, or in proximity to, this aquifer. The regional fluid flow system known to occur in this unit (Section 3.2), and evidenced by brine springs in the Devonian outcrop belt, is a further reason for suggesting that the Winnipegosis Formation be reserved for brine supply purposes. Because the formation fluids are derived at least in part from solution of the Prairie Evaporite salt and potash beds, it seems probable that the Winnipegosis brines may contain the highest amounts of potentially usable trace elements such as bromine and iodine.

Since detailed trace element analyses of formation fluids generally are not available, such analyses should be obtained prior to undertaking any waste disposal program to ascertain if the fluids have any economic potential. Furthermore, trace element analyses should be obtained for all formation fluids tests so that a regional background data base can be established.

## TABLE IV

**COMPOSITION OF BRINES IN THE WINNIPEGOSIS FORMATION — UTILIZED BY HOOKER CHEMICALS LTD. AT BRANDON, MANITOBA**

| | ppm | | ppb |
|---|---|---|---|
| Na | 63,000 | Fe | 405 |
| Cl | 123,366 | Cu | 5.0 |
| Ca | 2,650 | Zn | 18.1 |
| K | 2,200 | Ni | 1.2 |
| Li | 21.5 | Pb | 1.0 |

Analyses by Manitoba Mineral Resources Division, Dec. 1977.

### 7.7 "Thermal" Formation Fluids

The temperature of subsurface formation fluids is determined by the local or regional geothermal gradient. In some areas (e.g. Iceland, New Zealand, California) local geothermal gradients associated with nearby volcanic or igneous activity are very high and can give rise to very hot formation waters that can be used directly as heat sources or for electrical power generation. No such areas are known in Manitoba, where the geothermal gradient is relatively low and uniform. Nevertheless, at the maximum depth of sedimentary strata in the southwestern corner of Manitoba, formation waters attain temperatures in excess of 134°F. Although such "low level" thermal fluids cannot be used directly, heat-pump technology can be used to upgrade the thermal level for possible domestic or industrial use. Such low-level thermal formation fluids must therefore be considered as a potential subsurface resource. Even near-surface groundwater has sufficient heat content to be useful for this purpose.

### 7.8 Alternative Methods of Disposal

Dennison and Simpson (1973) reported that alternative surface methods of disposal would cost at least 2 to 3 times the total ultimate capital investment in each subsurface-disposal facility in operation at that time in the northern Williston Basin region. In Manitoba, the cost advantage of subsurface disposal may be reduced somewhat, since many industrial operations based in the southeast would have to take into account the increased costs relating to transportation of the wastes to the nearest permissible disposal sites which, as will be shown later, are located in the southwestern corner of the Province.

Canadian Salt Company's commercial production of sodium chloride from waste portions of the potash brines generated by Kalium Chemicals Limited at Belle Plaine, Saskatchewan, described by Simpson and Dennison (1975), is an outstanding example of reduction of wastes through co-operation between companies. The feasibility of a similar arrangement might be considered in future, as an alternative to subsurface disposal should potash production begin in Manitoba. "Waste" salt from potash mines in Saskatchewan is also currently used at the Hooker chemical plant east of Brandon, replacing salt formerly derived from subsurface brines.

# 8.0 DETAILED HYDROLOGIC EVALUATION OF SUBSURFACE DISPOSAL POTENTIAL IN MANITOBA

### 8.1 General Statement

Subsurface disposal of liquid industrial wastes has been carried out in a limited number of waste disposal projects in southwestern Manitoba (Section 6.3) with no known adverse effects to date. This suggests that this method of disposal is a viable alternative for Manitoba. Evaluation of the previously described geologic framework of Manitoba, utilizing the parameters outlined by van Everdingen and Freeze (Table I), supports this contention. It must be stressed, however, that subsurface disposal is *not* the best dispoal alternative from a purely environmental standpoint. As pointed out in the Introduction, the best method of waste handling is destruction or elimination (e.g., recycling) of the waste, *if such treatment is technically and economically achievable.* When waste elimination is not feasible, most commonly because of economic considerations, the subsurface disposal option becomes, in the writer's opinion, one of the prime alternatives for at least certain types of liquid industrial waste disposal. (The terms "waste storage" or "containment" are possibly more accurate than "disposal').

The following is an attempt to evaluate systematically, in general terms, the potential for subsurface waste disposal in the various regions previously outlined in Manitoba. It must be stressed, however, that this evaluation is a generalized treatment of a highly complex problem. Any "favourable" recommendations must be considered as tentative, and further detailed evaluation would be required for any proposed specific disposal site. Although areas and zones herein designated as potentially favourable for disposal may, on closer examination, turn out to be unacceptable, those areas and zones herein designated as unacceptable for waste disposal are much better defined and probably will remain unacceptable in any more detailed evaluation. The disposal potential map (Fig. 16) and the disposal potential cross-section (Fig. 18) summarize results of the evaluation for southwestern Manitoba.

### 8.2 Disposal Reservoir Requirements

Before discussing the potential of the various disposal zones, it is necessary to recap the basic requirements for a suitable disposal aquifer:

a) The disposal zone must have adequate porosity, permeability and volume to accept the necessary waste volume at the desired disposal rate. Porosity can be natural or artificial (induced fractures, solution).
b) The waste must be "compatible" with both the formation fluid and with the framework rock of the disposal zone or, alternatively, any waste interaction with the reservoir must be controllable. (It will be shown in Part II of this report that waste/formation-fluid interaction can be used to advantage in some instances).
c) The disposal reservoir, ideally, should be stratigraphically and hydrologically isolated from the biosphere. Factors determining the degree of isolation are, in estimated rank of importance:
   - impermeable cap rock and seat seal are adequate to confine waste to disposal zone;
   - stratigraphic isolation, i.e. reservoir strata do not extend to surface, as in stratigraphic truncation-type traps;
   - minimal regional flow of formation fluids in disposal zone;
   - structural integrity of reservoir beds, i.e. absence of fractures associated with local structural anomalies;
   - adequate depth from surface, and distance from outcrop — especially important if reservoir stata are not stratigraphically isolated;
   - lithofacies changes forming porosity and permeability barriers restricting intraformational fluid migration.

It should be noted that the depth of burial of potential disposal aquifers is considered, in many cases (and correctly), to be the prime factor in determining disposal suitability, since the thicker the section the greater the potential for barriers to vertical fluid migration. This is *not* believed to be the case in Manitoba, as indicated in the above listing. In the southwestern part of Manitoba the most deeply buried aquifers are open, or continuous to the outcrop belt, and at least some of these aquifers are also subjected to regional updip movement of formation fluids. The degree of isolation of these deep aquifers is deemed to be somewhat less than for the shallower but "stratigraphically isolated" (closed) aquifers. This admittedly is a subjective judgment since the deeper burial of the open or stratigraphically continuous aquifers (up to 600 m of added depth) must be balanced against the potential for updip migration due to formation fluid flow, where the distance to "outcrop" can be as much as 400 km for the deepest of the open reservoir beds — the Winnipeg Formation.

### 8.3 Subsurface Space Categories

In their study of the subsurface-disposal potential of Saskatchewan, Simpson and Dennison (1975, Table 20, p. 67) presented a speculative table relating seven main categories of subsurface space to types of waste which might be confined or contained in them, and assigning a "recommended waste-management status" to each category. Table V is essentially a revised version of their earlier table, modified in format for the specific geological setting of Manitoba. The following discussion deals largely with categories 1 and 2, natural intergranular (clastic) porosity and natural carbonate porosity.

### 8.4 Model for Designation of Proposed Disposal Regions and Zones

For ease of identification and reference, Manitoba has been divided into four regions, designated A to D, for evaluation of the overall potential for subsurface disposal of liquid industrial wastes in natural porosity. Within these regions, a number of hydrologically defined subregions or areas can also be designated (e.g., Aa), as discussed in the earlier stratigaphic section of this report. The main regions coincide approximately with the physiographic subdivisions of Manitoba. Within each region, the stratigraphic succession is subdivided into as many as three designated zones (I — III), corresponding to the previously described hydrostratigraphic units. For southwestern Manitoba, these zones are the basal clastic zone, the carbonate-evaporite zone and the upper clastic zone, respectively. (A somewhat different designation is indicated for the Hudson Bay area). Subzones (e.g., IIa) are also designated, based on the structural and stratigraphic constraints previously outlined. This dual identification permits designation of a series of alphanumerically identified sedimentary blocks or prisms (map units), each of which can be assigned a *relative* value with respect to disposal potential. For example, the map unit showing the best disposal potential in Manitoba is designated as AaIIb. Region Aa comprises the southwestern portion of the Southwestern Upland, where salt beds are preserved and possibility of salt collapse structural disturbance is minimal; Zone IIb comprises the uppermost portion of the carbonate-evaporite unit, which forms a confined or stratigraphically isolated reservoir unit that does not extend to surface. Designation of disposal units is shown in Figure 17.

Distribution of the above proposed disposal map units is shown in Figure 16 and the estimated relative suitability of disposal potential is shown in Figure 18. The basis for this proposed valuation is discussed below. The valuation is based primarily on geotechnical considerations as to the degree of reservour containment; it does not consider the severity of the results of containment failure in terms of the possible number

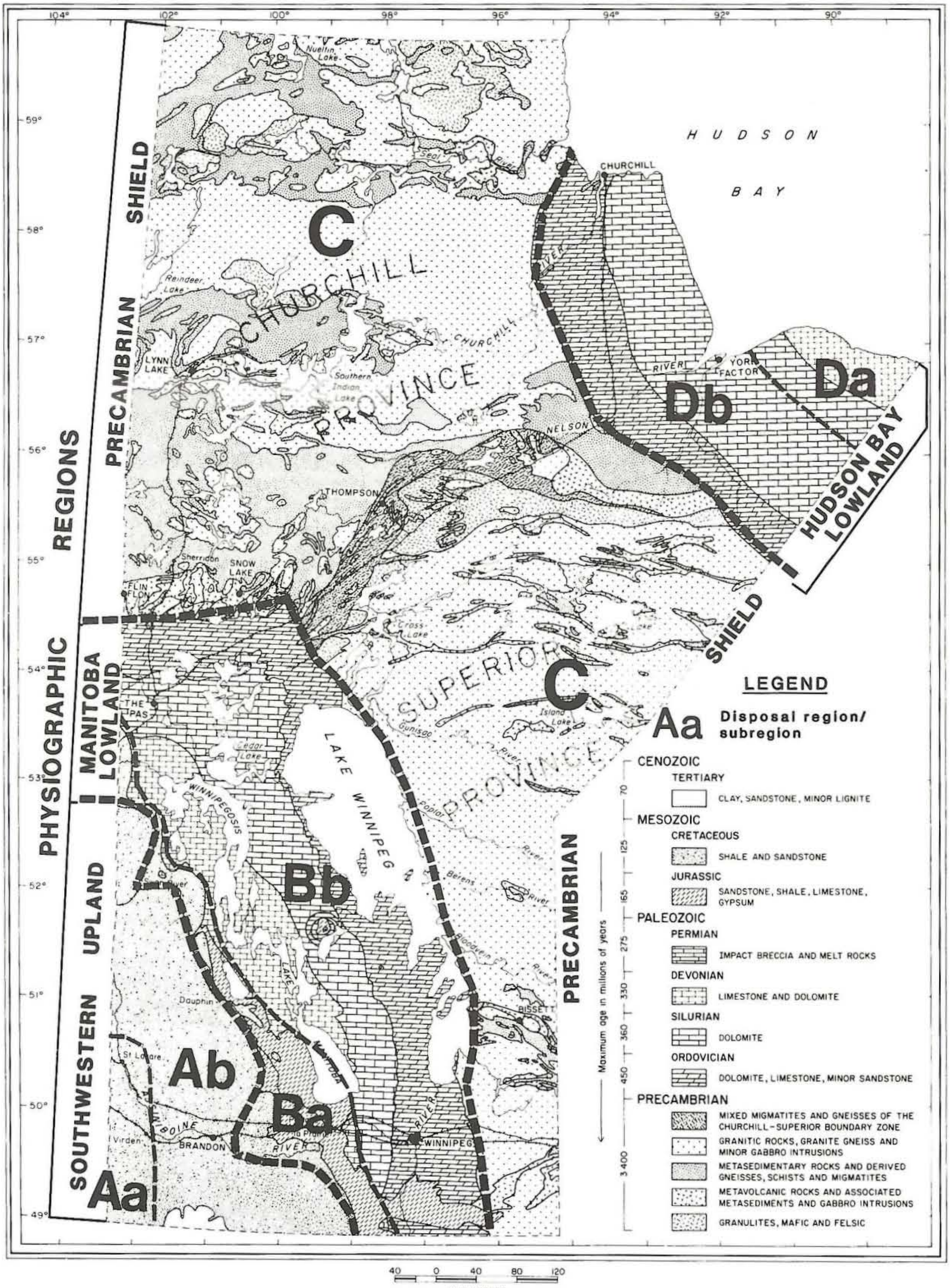
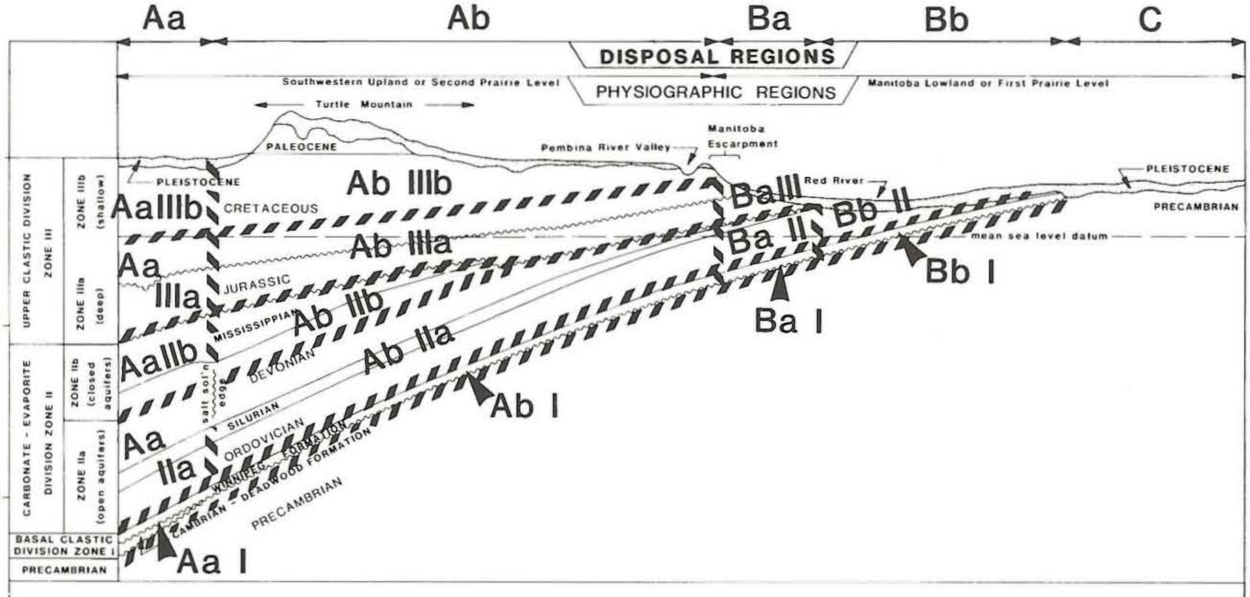



*Figure 16 Designation of disposal regions and sub-regions, Manitoba.*




## SUMMARY DEFINITIONS

### DISPOSAL REGIONS

**A** - Southwestern Upland physiographic region (thick shale cover)

- **Aa** - portion presently underlain by Devonian salt beds (minimal collapse structures)
- **Ab** - portion beyond present limit of Devonian salt (solution collapse area in part)

**B** - Manitoba Lowland physiographic region (shale cover thin or missing)

- **Ba** - southwestern portion with thicker sedimentary section and more numerous aquitards
- **Bb** - northeastern portion with thin sedimentary section and few aquitards

**C** - Precambrian Shield - no sedimentary bedrock

**D** - Hudson Bay Lowland

- **Da** - thicker basinward portion underlain by Kenogami River aquitard
- **Db** - thinner marginal portion no major aquitards, partial drift cover

### DISPOSAL ZONES

**I** - Basal Clastic Unit (Winnipeg and Deadwood Formations)

**II** - Carbonate - Evaporite Unit (Ordovician Red River to Mississippian Charles Formations)

- **II a** - lower portion of unit; beds extend to outcrop (open aquifer)
- **II b** - upper portion of unit; beds truncated in subsurface (closed or isolated aquifer); includes Duperow and younger Paleozoic formations

**III** - Upper Clastic Unit (Mesozoic and Cenozoic)

- **III a** - lower portion of unit, to top of Ashville Sand; includes all significant porosity zones except Boissevain Sandstone
- **III b** - upper portion of unit; no appreciable porosity except for Boissevain Sandstone

*Figure 17 Designation of disposal units, southern Manitoba.*

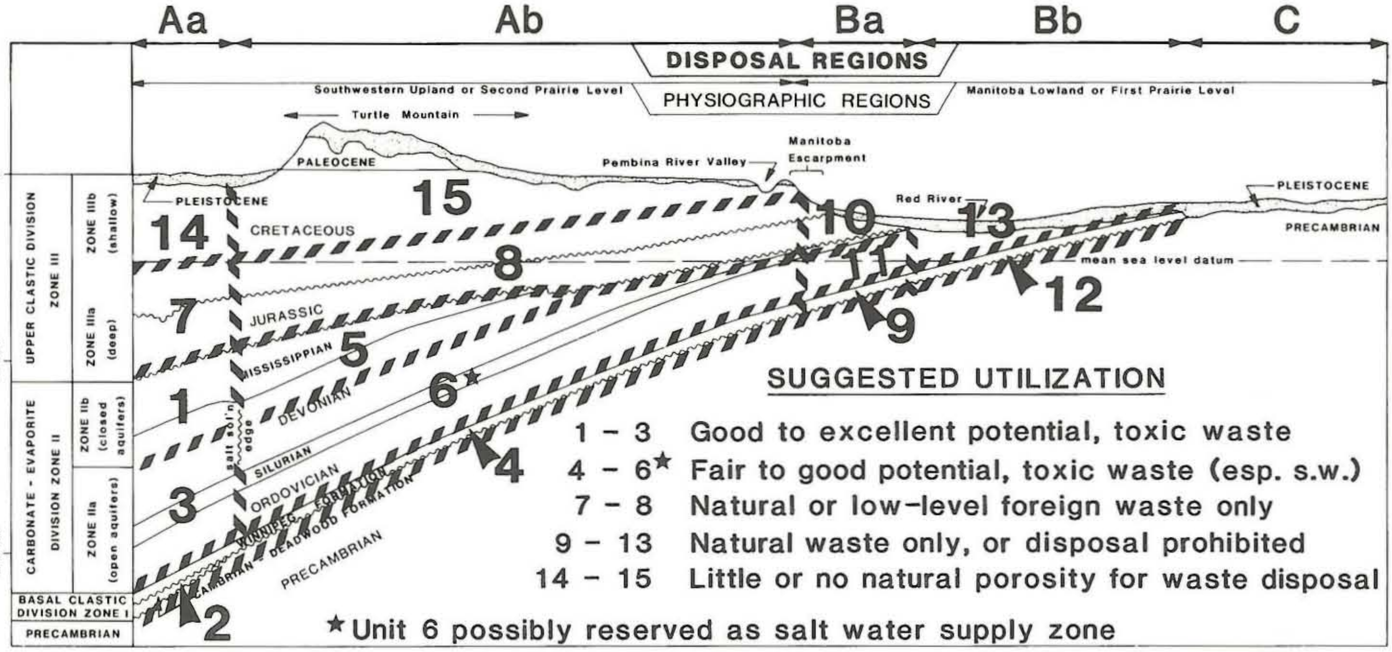



*Figure 18 Regional disposal-potential cross-section, southwestern Manitoba.*

of people affected. This latter factor is beyond the scope of this report, except in general terms, but is nevertheless a very important aspect in the overall evaluation of any specific disposal site.

**8.5 Regions and Zones not Recommended for Subsurface Waste Disposal**

The following areas are deemed, at the present time and with the presently available data base, to be generally unfavourable for subsurface waste disposal, although limited potential does exist for disposal of "low level" or natural waste into deeper zones in some portions of these regions.

**8.5.1 Precambrian Shield — Region C**

This region has not been discussed previously in this report because sedimentary strata are lacking. Consequently subsurface disposal into natural porosity in bedrock formations is severely limited because of the generally low porosity and permeability of the Precambrian rocks. Moderate permeability (i.e. water production) is known to occur in Precambrian rocks (R. Betcher, Water Resources Branch, pers. comm.) but such occurrences tend to be local, and probably result from open fractures connected to surficial aquifers. Potential for disposal into artificial porosity (e.g., mined excavations), however, is high and is being studied intensively as a prime possibility for high-level radioactive waste disposal or containment. In this case the level of fracture permeability in the Precambrian basement rocks is considered detrimental, and becomes a critical factor. Evaluation of such subsurface disposal in artificial openings is beyond the scope of this paper. The Underground Research Laboratory (U.R.L.) presently being established by Atomic Energy of Canada Limited (AECL) near Lac du Bonnet, Manitoba, will evaluate in detail some aspects of the potential for radioactive waste disposal in a massive granitic pluton.

Limited disposal of fluid waste into porous surficial deposits (glacial and fluvioglacial sands and gravel) is a possibility, but the proximity of these beds to the near-surface groundwater and river flow systems severely limits such disposal potential. The optimum disposal configuration would require a closed basement (bedrock) low in an area with no active surface drainage. Such a configuration probably is rare and would be difficult to define, but would provide a reasonable level of containment. In general, however, the potential for subsurface waste disposal in Region C is minimal, although the "people effect" of containment failure in this area would be low because of the generally sparse development. Local ecological and downstream effects could nevertheless be serious.

**8.5.2 Manitoba Lowland, Region B (map units BI, II)**

This region comprises all of the Manitoba Lowland, and includes all Ordovician, Silurian and Middle Devonian strata (Zones I, II) in the designated area. The considerable diversity of industrial development, particularly in the Winnipeg district, and the presence of a number of deep aquifers ensure interest in deep well injection as a possible waste-disposal option. Unfortunately, the potential for subsurface disposal in Area B is limited, and for most of the area subsurface disposal of foreign wastes should not be permitted. Near the southwestern boundary of the area, however, a subarea Ba can be defined bounded roughly by the outcrop belt of the Ashern Formation. In this subarea the sedimentary section attains a thickness of up to 400 m, a thin Jurassic shale and evaporite cover is present, and impermeable interbeds within the carbonate-evaporite unit (e.g., Ashern shale) become thicker and more numerous, causing considerable limitation to vertical fluid migration. Emplacement of natural or even low level foreign wastes possibly could be considered in this subarea (Ba), particularly in the basal clastic unit (Ba-I). For the remainder of the area (subarea Bb), the relatively thin successions of strata of both the basal clastic and carbonate-evaporite units extend to surface, or outcrop beneath a thin cover of drift or glacial lake clays in most of the area. As noted previously, the carbonate strata of map unit BII can be considered to form a single hydrogeologic unit which forms the principal potable ground water aquifer throughout most of the region — the so-called "Carbonate Aquifer". Any waste emplaced in these carbonate strata in this area would almost certainly be incorporated eventually into the surficial groundwater system.

The basal clastic beds of the Winnipeg Formation in this area (Map unit Bb-I) show reasonably good reservoir isolation from the overlying "Carbonate Aquifer", at least in the southern portion of area B (see section 5.2), and the formation fluids in the southwestern portion of the area are moderately saline (Fig. 9). The Winnipeg Formation thus could be considered for subsurface disposal of *natural* waste in those areas where the formation waters are too saline to be of commercial or domestic use. The Dorsey disposal project falls in this category (Section 6.3.4). Disposal of *foreign* or toxic waste, however, should not be permitted anywhere in subarea Bb.

The southern portion of area B, and in particular the Winnipeg area, is the most highly industrialized part of the Province and will have the greatest need for new subsurface disposal facilities for foreign and toxic waste. Since disposal of such waste should not be permitted in this area, this means that *off-site disposal of toxic wastes will be required*, with all of the attendant economic and logistic problems involved in surface transportation of the waste. Although off-site disposal raises some problems, it also provides the potential for choosing the best possible locations for off-site disposal facilities, and possible establishment of a composite facility or disposal field for injection of wastes from a number of different sources. This also underscores the desirability of some type of industrial zoning, so that industries generating appreciable quantities of toxic liquid wastes would be required or requested to locate in areas where direct on-site disposal could be implemented.

### 8.5.3 Hudson Bay Lowland — Region D

The Hudson Bay Lowland (Region D) possesses a number of geologic and hydrologic features favourable to subsurface waste disposal. These include the relatively thick Paleozoic succession (up to 1000 m); the occurrence of a medial sequence of impermeable shaly beds; the lack of seismic activity; the apparent lack of structural deformation; the generally thick mantle of impermeable glacial till (45 - 120 m); and the stratigraphic isolation of the basin, with lack of uplifted hinterlands that could give rise to regional flow of subsurface fluids. A possible alternative aquifer use would be for natural gas storage for far north gas. Of course, the need for waste disposal facilities in this remote northern area is not foreseen in the immediate future, but clearly any future feasibility study related to any specific disposal or storage system must take into account the unique and poorly understood groundwater regime of a permafrost region, since water supply must assume a priority higher than that assigned to waste disposal.

Within the Hudson Bay Basin area (Region D, Fig. 17), two subareas can be designated by the approximate limits of the Lower Silurian Kenogami River Formation. Northeast of this limit, in subarea Da, the lower Paleozoic strata (Zones I, IIa) occur beneath the relatively impermeable clastic beds of the Kenogami River, and seem to offer reasonable potential for subsurface disposal, although these strata extend to outcrop. The upper portion of the carbonate sequence in this subarea (Zone IIb) is too close to surface and the till mantle at least locally too thin to permit subsurface disposal. For the remainder of the area, Db, the sedimentary sequence is relatively thin. Good aquitards are not present, other than the generally thick cover of glacial till, which in places is deeply incised along the main river channels. The disposal potential is marginal at best in area Db, and not recommended.

In summary, limited potential for waste disposal has been shown for parts of the Hudson Bay Lowland area, on the basis of regional structural and stratigraphic data. However, the extreme lack of detailed geological data places sufficient doubt on the disposal potential that the region has been included in the "not recommended" category. Specifically, because of the pronounced paleotopographic basement high outcropping in the Churchill townsite area, and the local exposure of Paleozoic and Precambrian strata at surface, this area should be excluded from any type of subsurface waste disposal.

### 8.5.4 Southwestern Upland — upper clastic division — map unit AIII

This zone comprises all Jurassic, Cretaceous, Cenozoic and Quaternary strata in the designated area (Fig. 16, 18). For most of the region, the sedimentary sequence is too thin, the formations have too few porosity zones, and the strata are too close to surface to be considered for subsurface disposal. Furthermore, as noted previously, these strata, particularly in subarea Ab, show a close spatial coincidence of modern fluvial valley systems and ancient antecedent systems, controlled in large part by salt solution phenomena. In these areas, fracture-bounded sinks, formed through local solution of Middle Devonian evaporite beds, could constitute conduits for easy upward movement of waste fluids under pressure. Waste injection in proximity to such features also would present the possibility of injection-induced crustal instability as a result of "lubrication" of fracture zones.

As in the case of carbonate sediments of the Manitoba Lowland, the upper clastic sediments (Zone III) of the Southwestern Upland thicken to as much as 1075 m to the southwest, and aquifers in the lower portion of the sequence become somewhat better developed, particularly the Swan River and Ashville Sands (Fig. 13). For that portion of the Southwestern Upland west of the present Devonian salt limit (designated as subarea Aa), and hence in the area where salt collapse has not occurred or is of only limited extent, disposal of natural waste or possibily low-level foreign waste could be considered in the lower portion of the upper clastic zone (IIIa). For example, salt water disposal of oilfield brines was carried out for a time in the Cretaceous Ashville Sand of the Virden area, but had to be terminated because of over-pressuring of the disposal zone. Such disposal, however, would be a poor choice since a wide range of disposal zones are present at deeper levels in the same area, as outlined below.

## 8.6 Regions and Zones Favourable for Subsurface Disposal

All of the previously discussed regions/zones have at best limited possibilities for subsurface disposal especially for foreign toxic waste, and some areas, in particular the Manitoba Lowland with its high population density, probably should be excluded totally from any subsurface disposal of toxic or foreign wastes. Disposal of natural wastes under suitable conditions can be accepted (e.g., Dorsey, Section 6.3.4). In marked contrast, the zones or map units described below generally are favourable for subsurface disposal because of the distinctly different geologic and hydrogeologic configurations outlined previously, which can provide an order of magnitude greater potential reservoir containment or isolation. The last described unit in this section (AaIIb) is believed to provide close to optimum conditions for subsurface liquid waste containment.

Each zone is discussed below, in order of estimated increasing degree of disposal potential.

### 8.6.1 Southwestern Upland — lower zone of carbonate-evaporite division — map unit AIIa

This map unit comprises all Paleozoic carbonate strata from the Ordovician Red River Formation up to and including the Devonian Souris River Formation (Fig. 5), within the designated area (Fig. 16). The potential disposal strata are deeply buried and separated from the surface by up to 1000 m of dominantly argillaceous Mesozoic clastics (Zone I), as well as up to 500 m of carbonates, evaporites and shales comprising the upper part of the carbonate-evaporite division (Zone IIb). Excellent porosity and permeability are present in various stratigraphic units within this sequence. As noted previously, the principal negative factor with regard to disposal potential is that these strata are continuous to outcrop, and consequently any regional updip flow of formation fluids or updip waste migration could eventually transport the waste into the near-surface potable groundwater regime. The distance from potential disposal areas to outcrop, however, is as much as 300 km in the case of the deepest carbonate zones, and the time frame for any escape of waste to the biosphere would be extremely long. The complexity of lateral lithofacies changes in these carbonate strata and the related variations in porosity and permeability also would no doubt tend to restrict waste migration. Nevertheless, the possibility of such waste migration, however slow, tends to downgrade the disposal potential of these strata.

In particular, the previously noted high rate of regional fluid flow in the Winnipegosis Formation, as evidenced by the extensive brine springs along the northern part of the Manitoba outcrop belt and also by the high artesian head noted in a number of shallow stratigraphic core holes, would seem to downgrade severely, if not preclude, any disposal of "foreign" wastes into the Winnipegosis Formation. Regional flow also has been reported in Silurian strata of central Saskatchewan (Wilson et al., 1963), so the disposal potential of this unit also must be downgraded somewhat. Although the above-noted regional flow systems undoubtedly affect the northern part of the area in question, it is by no means clear if the effect of these systems extends to the southern part of the area (i.e. in the "lee" of the remaining salt beds). Detailed hydrodynamic studies are necessary to determine if such a regional flow system exists in this area.

Because of the known occurrence of a regional flow system, and the high salinities in the Winnipegosis Formation, it was suggested earlier in this report that the Winnipegosis possibly could be "reserved" as a brine aquifer rather than utilized as a waste disposal zone. If this suggestion is followed, disposal potential of adjacent strata (Silurian and Middle Devonian) would also be downgraded because of the probability of cross-formational flow, and this would remove much of the lower portion of the carbonate-evaporite division from the list of potential disposal zones.

**8.6.2 Southwestern Upland — basal clastic unit — map unit AI**

Includes the Cambrian Deadwood and Ordovician Winnipeg Formation in the designated area (Fig. 5 and 18). These beds are the deepest of the potential disposal zones, being overlain by up to 2300 m of sedimentary strata. However, as noted previously, these strata extend to outcrop, a factor that tends to downgrade the disposal potential. The regional lithofacies pattern shown by the Winnipeg strata (McCabe, 1978) suggests that regional updip flow of formation fluids may not be as much of a potential problem as in some of the overlying lower Paleozoic carbonates. In general, the sands of the Winnipeg Formation are a basin-margin or shoreline facies, and except for a thin basal sandstone, do not extend into the deeper basinal areas. This central-basin shale barrier would appear to limit the possibility of any regional, cross-basin flow. However, the facies distribution at the same time limits the thickness of available sand aquifers in the most favourable (deepest) southwestern area. Here again, detailed potentiometric evaluation of available data should be carried out to evaluate the possibility of regional fluid flow.

In the northern part of the Southwestern Upland, the Winnipeg Formation becomes increasingly more sandy, with attendant improvement in aquifer quality, but the depth of burial decreases, and the sands become a thick, blanket-type deposit. The intermediate facies, located in the general vicinity of latitude 51°N, shows a complex interbedding of sand and shale, and possibly is the most favourable area for waste disposal, particularly if the sands are isolated bar-type deposits and are not continuous updip with the main sand of the northern shelf area.* Data are not adequate to determine the precise nature of the sand distribution.

The basal clastic unit has one other characteristic that sets it apart from most of the other potential disposal zones in Manitoba. The aquifer beds are almost pure silica sand, generally highly porous and permeable, and largely uncemented. These beds will thus be relatively inert as far as any possible reaction with waste fluids. This could be an important factor in disposal of reactive-type wastes. However, porosity enhancement by standard HCl acid leaching (normal oil well procedure) would not be possible in the non-calcareous sandstone aquifers.

The excellent porosity, maximum depth of burial, probable absence of appreciable regional updip fluid flow, and the inertness of the reservoir framework all would seem to indicate that this zone (Aa/I) is only slightly less favourable as a disposal zone than the upper Paleozoic zone (Aa/IIb) of the same area.

*A recent test hole in Lsd 15-11-12-26WPM cored an oil-stained interval in a sandy interbed in the Winnipeg Formation, in the above noted area of complex sand/shale interbedding. This would seem to support the suggestion that some sand beds may not be continuous updip.

**8.6.3 Southwestern Upland — upper zone of carbonate-evaporite division — map unit AIIb**

This zone provides the best disposal potential available in Manitoba; it includes all upper Paleozoic Formations, from Devonian Duperow up to and including Mississippian Charles Formation (Fig.5), in the designated area (Fig. 16, 18). These strata are buried beneath as much as 1075 m of largely impermeable Mesozoic clastics of the upper clastic unit. In addition, the beds are truncated at the pre-Mesozoic unconformity surface so that the formations *do not extend to outcrop*. The relatively high salinity of formation fluids in these strata, as well as the presence of oil accumulations trapped immediately beneath the unconformity surface of Mississippian strata, provide a measure of the degree of reservoir isolation.* As a result, regional flow of formation fluids in these formations is highly restricted or non-existent. All other Paleozoic formations (i.e., Zones I, IIa) extend to outcrop, and show a progressive decline in formation water salinity towards the outcrop belt, indicative of some measure of interconnection with the surficial groundwater regime.

Even though the strata of this zone (IIb) are not as deeply buried as the underlying portion of the carbonate-evaporite zone (IIa) or the basal clastic zone (I), the greater degree of stratigraphic isolation, and hence hydrologic isolation, suggests that these upper Paleozoic carbonates are the *best possible choice for subsurface disposal of liquid industrial waste* in Manitoba, provided there are no local negative structural factors.

For the upper Paleozoic aquifers of zone IIb, a further areal distinction must be noted with respect to disposal potential — the same distinction that was noted for the upper clastic unit. The area west of the present Devonian salt edge (subarea Aa), where salt solution has not occurred or is of only limited extent**, affords significantly better disposal potential, not only because upper Paleozoic and Mesozoic strata have not been subjected to fracturing as a result of salt collapse, but also because the sedimentary section is appreciably thicker. Furthermore, in the southern portion of the subarea, additional aquitards are present, most notably the upper Mississippian "Charles" evaporites (Fig. 5). The optimum disposal area thus appears to be the southwestern portion of subarea Aa, particularly where the Charles evaporites are present.

Potential disposal horizons within the upper part of the carbonate evaporite sequence zone (IIb), in particular the Devonian Nisku Formation and the MC-1 and MC-3 members of the Mission Canyon Formation (Fig. 5), show excellent porosity and permeability. Nisku strata have so far proved to be barren of any petroleum accumulation. Mission Canyon strata are oil-bearing in a number of localities (McCabe, 1963) in stratigraphic and structural/stratigraphic traps at or near the subcrop edges of both the MC-1 and MC-3 members of the Mission Canyon Formation (Fig. 5). Mission Canyon strata generally show the best overall porosity and permeability, and the large stretches of the subcrop belts that have proved to be barren of oil accumulation should provide good potential for disposal sites. Because of the differing behaviours of waste and petroleum in the subsurface environment (Section 8.9), the downdip portions of all of the above-noted aquifers also can constitute excellent potential disposal sites.

One additional factor favours disposal in the Mission Canyon Formation as compared to stratigraphically (and structurally) lower units such as the Nisku Formation. Although all stratigraphic units comprising Zone IIb are truncated at the unconformity, fluids migrating updip in these units will be trapped at the unconformity only where stratigraph-

* Refer to footnote, section 5.3.2, re: leakage from Mississippian reservoirs.

**Recent well data indicate that major salt collapse features may be more common in subarea Aa than previously thought.

ically lower impermeable beds form a "seat seal", preventing further updip migration along the unconformity. The shaly beds of the Upper Lodgepole, and more importantly the Bakken-Lyleton shales, form excellent seat-seals for the Mission Canyon, as shown in Figures 5 and 6. In contrast, seat-seals below the Nisku Formation are much less effective.

The best disposal zone in southwestern Manitoba appears to be the MC-3 member of the Mission Canyon Formation in the extreme southwestern corner of the province, at depths of 900 to 1100 m. The MC-3 reservoir beds there are capped directly by up to 40 m of impermeable Charles evaporite, as well as up to 1075 m of the upper clastic unit (Mesozoic). The depth, nature of the cap rock, lack of regional formation fluid flow (stratigraphic trap configuration), location beyond the area generally affected by Devonian evaporite solution (structural integrity), and the excellent porosity and permeability all contribute to the optimum disposal environment. The only negative factors appear to be economic and relate to cost of drilling to such depths at locations distant from the waste-generation facilities. The latter factor could be avoided if the area were to be designated for preferential location of industries producing appreciable quantities of toxic liquid wastes. Surficial environmental impact would have to be considered, however, prior to implementation of any such plan.

For subarea Ab, the disposal potential is believed to be good, but nevertheless significantly lower than for subarea Aa. The entire sequence of upper Paleozoic carbonates in subarea Ab (Zone IIa) probably has been subjected to some degree of salt solution and collapse, which will have reduced the structural integrity of the Paleozoic reservoir beds. However, the thick Mesozoic cover and the impermeable dolomite/anhydrite alteration zone at the Paleozoic unconformity appear to provide an adequate cap rock, and the beds do not extend to outcrop. Acidic waste capable of dissolving the evaporite cap rock (anhydrite) could pose a problem, but carbonate minerals commonly associated with the anhydrite probably would neutralize the acid.

**8.7 Local Restrictive Factors**

The areas/zones outlined in section 8.6 are generally favourable for subsurface disposal. However, a number of *local* structural and stratigraphic anomalies, most of which have been discussed in detail earlier, can severely affect the degree of containment at specific localities within an otherwise favourable disposal area. Such features should be strictly avoided. In summary, these unfavourable features include:

a) Salt collapse structures: especially younger structures affecting nearer-surface formations (post-Paleozoic); most common along Birdtail-Waskada Axis (Fig. 7).
b) Crypto-explosion structures (Fig. 7).
c) Reefal structures: especially where associated with salt collapse. Overlying collapsed strata undergo maximum deformation. Common along Birdtail-Waskada Axis (Fig. 7).
d) Tectonically derived structures: possibly Birdtail-Waskada Axis.
e) Differential compaction structures: associated primarily with the Winnipeg Sand and the Ashville Sand.
f) Positive relief features on the Precambrian erosion surface: resulting in differential compaction structure in the overlying Phanerozoic succession. Such features could deflect the injection-augmented flow of formation waters and wastes upwards, thus promoting cross-formation flow. To date, however, such positive relief features have not been identified in Manitoba.
g) Ancient valley systems: escarpments and local relief features incised at the karstic sub-Mesozoic unconformity. Such features can give rise to differential compaction structures and also result in sedimentary anomalies in overlying strata. For example, antecedent pre-Mesozoic valley systems coincide spatially with, and apparently have exerted strong control on, patterns of younger fluvial valley systems of Early Cretaceous, Late Cretaceous-Tertiary, Pleistocene and Holocene ages. These largely parallel valley systems impart a considerable anisotropy to flow of formation waters.

A further, non-geological restrictive factor could be the presence of improperly abandoned oil exploration wells, particularly those dating back to the early years of exploratory drilling. Fortunately, comprehensive well records are available for Manitoba, and proper abandonment procedures have been enforced for all but the earliest holes. Nevertheless, it is advisable to check with the Petroleum Division of Manitoba Energy and Mines to obtain information on any drilling that has been carried out in the vicinity of a proposed disposal site.

**8.8 Hydrocarbon Prospects as Potential Disposal Sites**

Once a favourable region or zone for possible waste disposal has been defined, the next phase of any proposed subsurface disposal program would be directed toward location of specific drilling targets. Such targets consist of strata with adequate reservoir quality, occurring in structural-stratigraphic trap configurations generally similar to those sought as hydrocarbon prospects (Dennison and Simpson, 1973; Simpson and Dennison, 1975). Obviously, the drilling targets for deep-well disposal must not contain commercial accumulations of hydrocarbons, but many of the drilled hydrocarbon prospects designated as "geologic successes" but "economic failures" (i.e. "dry holes") (Hardin and Mygdal, 1968) could be prime waste-disposal prospects. For a detailed discussion of potential oil exploration targets, the reader is referred to Christopher et al. (1971, 1973). Their accounts deal with the oil exploration potential of Saskatchewan, but the outline for the Paleozoic sequence of Saskatchewan is largely applicable to Manitoba as well.

Although prospective hydrocarbon traps, such as those outlined by Christopher et al. (op. cit.) can comprise suitable disposal sites, problems can arise from the differences in behaviour of waste and hydrocarbons in the subsurface environment.

**8.9 Different Behaviours of Oil and Liquid Waste in the Subsurface**

Barren oil traps and depleted oil fields can be considered as possible sites for subsurface waste disposal. However, hydrocarbons and waste may tend to migrate differently in the subsurface. Oil, because of its low specific gravity, tends to migrate up the structural gradient; wastes, on the other hand, may show no such tendency and could tend to migrate downwards (downdip) in the case of high-density wastes. The latter behaviour would be highly beneficial for disposal purposes since waste movement would be away from the biosphere. Another factor to consider is that hydrocarbons are immiscible with formation waters, and their migration is restricted to zones of higher permeability. Accumulations of hydrocarbons are controlled by capillarity relationships between nonmiscible fluids. Water-based wastes, however, are not so constrained, and could possibly be more mobile in the subsurface environment than petroleum. It is thus possible that some porosity, permeability and structural configurations suitable for oil entrapment could prove to be more effective, less effective, or even ineffective for waste containment.

For example, consider a potential oil trap in a Winnipegosis reef in an area where an active regional flow of formation fluids is presently taking place, such as in Manitoba. Oil could be trapped in such reefal structures because its low specific gravity (buoyancy) and immiscibility would prevent it from being carried downward and flushed out of the reef by the regional fluid flow. Waste, however, would not necessarily be under such buoyancy and immiscibility constraints, and would tend to be flushed out of the reef and eventually discharged at surface.

In view of the above, caution must be exercised in suggesting that all potential hydrocarbon traps are suitable as potential waste disposal sites. In general, structural traps may be suspect, and as pointed out by McLean (1968) should probably be reserved for alternative purposes such as natural gas storage. In contrast, stratigraphic truncation-type traps, which are the predominant type in southwestern Manitoba, appear to be eminently suitable as waste disposal sites, since not only is updip migration limited, but regional formation-fluid flow is restricted or prevented.

In effect, the different behaviour of waste and hydrocarbons greatly broadens the possibility for stratigraphic-type waste disposal sites. Oil accumulation in truncation traps requires some type of structural, paleotopographic or porosity closure so as to localize accumulation along the updip edge of a regional trap or subcrop belt. Otherwise, oil will migrate along the stratigraphic trap, up the regional structural gradient of the subcrop belt (because of the buoyancy effect). Since wastes generally will show no such buoyancy effect, disposal should be possible at any location along a regional unconformity trap, not just in those areas where closure provides a suitable site for oil accumulation. Furthermore, disposal need not be limited to the updip limits of such truncation traps; downdip sites would be equally effective.

**8.10 Alternative Methods of Subsurface Disposal**

In addition to the potential for disposal of liquid wastes in natural reservoir porosity, Manitoba has the opportunity to utilize a number of categories of artificial subsurface space, about which relatively little is known from the standpoint of hydrogeology. These space categories have been listed in Table V, where the need for further research is noted:

(1) The shales of the Winnipeg Formation could be rendered suitable for use as repositories for industrial wastes by hydraulic fracturing, followed by introduction of cement and minor quantities of fluid wastes. The theory of hydraulic fracturing and grouting as a mode of disposal for noxious wastes is discussed by Sun (1973). Only the thickest and most deeply buried sections of Winnipeg shales could be considered for this type of subsurface disposal. Locales with a high occurrence of thin sandstone and coarse siltstone intercalations in vertical succession would present a danger of lateral migration of wastes and should be avoided. The basinal shale facies occurring in the southwestern corner of the Province (subarea Aa), would seem to offer the best potential for this method of disposal.

(2) Artificial subsurface space in evaporite strata provides interesting possibilities for use in waste containment, and is being evaluated intensively for the storage of radioactive wastes in many parts of the world. In Manitoba, the space provided by mine workings of room-and-pillar type in evaporites has to date been restricted to Jurassic anhydrite-gypsum beds at shallow depths. Such excavations could have some future application in underground waste management, although their proximity to surficial groundwater aquifers, some of which are under artesian pressure, limits the disposal potential.

At the present time, the Middle Devonian Prairie Evaporite in Manitoba is without artificial subsurface space of this type, but the possibility of disposing of minor amounts of wastes into mining or solution caverns merits careful consideration for the future, although the potential for alternative resource utilization would have to be considered. Feasibility studies relating to this mode of disposal should pay particular attention to minor, though significant porosity-permeability gradients in evaporite strata, which Aufricht and Howard (1961) consider to be related to:

(a) the type and amount of impurity in halite, including shale and mudstone layers;
(b) the crystalline structure of the halite and orientation of cleavage planes;
(c) the confining or overburden pressure on the evaporite sequence; and
(d) the water content.

The migration of brine droplets in bedded salt deposits in response to thermal gradients, such as those around high-level radioactive wastes, is also a phenomenon of great importance. Work by Anthony and Cline (1973) has shown that liquid droplets migrate slowly up a temperature gradient towards a heat source, whereas biphase liquid-gas droplets (waste-contaminated!) migrate rapidly down thermal gradients, away from heat sources.

(3) The hydrogeology of the Precambrian Shield merits detailed study and is poorly known at the present.

## TABLE V

### WASTE-DISPOSAL POTENTIAL OF DIFFERENT TYPES OF SUBSURFACE SPACE IN MANITOBA

| | Subsurface Space Category | Stratigraphic Distribution | Recommended Underground Waste Management Status | Waste Categories for Underground Disposal | Optimum Disposal-Site Location | Remarks |
|---|---|---|---|---|---|---|
| 1 | Intergranular-siliclastic porosity | upper clastic division | restriction to oil-field systems | natural wastes at low pressure and low injection rate | hydrocarbon-producing locales | lower clastic division likely to be used by potash industry; observation wells needed |
| | | lower clastic division | good potential | natural wastes and non-radioactive foreign wastes | stratigraphic trap setting, deep basinal | |
| 2 | carbonate porosity, various types | carbonate-evaporite division | good potential (see detailed evaluation of sub-zones) | natural and foreign wastes | deeper basinal areas, no salt collapse | depleted hydrocarbon-producing locales provide high potential |
| 3 | hydraulically-induced fractures | upper clastic division | unsuitable for permanent system | unsuitable | | experimentation on fracturing and grouting necessary; observation wells needed |
| | | lower clastic division | good potential but experimentation necessary | foreign waste and possibly low level radioactive waste | thickest shale sections at maximum depth | |
| 4 | excavations in igneous and metamorphic rocks | Precambrian basement, Shield area | good potential | low level to high level foreign and radioactive wastes in metal and/or concrete containers | uninhabited Shield area with minimal surface and groundwater flow | unfractured rocks only; continuous monitoring necessary |
| 5 | excavations in evaporite beds | Amaranth Evaporite (anhyd.) of upper clastic division | fair potential | low level foreign waste | abandoned mine workings | proximity to surface a problem |
| | | Prairie Evaporite unit of carbonate-evaporite division | good potential | toxic foreign and possibly radioactive waste | mined out potash production site | continuous monitoring necessary |
| 6 | caverns from controlled solution of evaporite strata | Prairie Evaporite unit of carbonate-evaporite division | fair to good potential | toxic foreign waste and possibly low- to high-level radioactive waste, in containers | deepest areas; possible use of mined-out solution mining site | continuous monitoring necessary |

# 9.0 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Regional evaluation of the potential for subsurface disposal of liquid industrial waste in sedimentary strata of Manitoba has shown that Paleozoic strata, particularly upper Paleozoic formations underlying the Southwestern Upland contain excellent potential disposal zones (Fig. 16, 18). In particular, dry holes drilled in petroleum exploration, and depleted oil-producing areas can provide suitable sites for waste disposal projects.

In contrast, the Manitoba Lowland area, underlain by a relatively thin sequence of Lower Paleozoic carbonates, generally is unacceptable for any type of subsurface waste disposal other than recycling of natural formation fluids. Inasmuch as this "unacceptable" area includes much of the industrial development in the Province (especially the Winnipeg area), and hence most of the waste generating facilities, subsurface disposal generally will be required at off-site localities distant from the sources of waste generation. The added expense and risk involved in transportation of waste to the disposal site will be offset partially by the opportunity to choose the best possible disposal site, and possibly also the added opportunity to utilize a common subsurface disposal facility for a number of different waste sources. A small depleted oil field could provide such a facility at minimum cost; the Maples 7-8-10-26 disposal well, discussed in Simpson and McCabe (in preparation: Part II of this report), is an example.

Within areas/zones designated as generally favourable for subsurface disposal (Fig. 17, 18), local structural and/or stratigraphic anomalies can seriously downgrade the disposal potential. Although the known types and occurrences of such features have been outlined in detail, comprehensive evaluation of any proposed disposal site to ascertain the existence of such features is essential; such evaluation must include test hole drilling and evaluation of all relevant reservoir parameters.

All alternatives to subsurface waste disposal must be considered to ensure that there is no viable alternative method of "disposal" (i.e. destruction or permanent neutralization of the toxic waste components — such as high temperature incineration, etc.). Subsurface space is a non-renewable and limited resource, and waste emplacement is irreversible and precludes any other future use of the resource.

No specific regulations have been enacted in Manitoba, to date, to control subsurface waste disposal projects, mainly because the need has not yet arisen to any extent. Nevertheless, the existing regulations preclude any subsurface disposal without specific government approval so that adequate safeguards can be applied to any proposed waste disposal project. Specific regulations have been outlined for Ontario (McLean, 1968) and relevant factors requiring regulation have been outlined briefly in this report. One aspect of regulation that must be stressed is the importance of monitoring disposal projects. Possibly consideration could be given, as required, to the drilling of a number of deep holes along the updip edge of the acceptable disposal region to detect any movement of waste towards the biosphere. Alternatively, deep oil-exploration dry holes, at suitable locations, possibly could be retained as monitoring sites rather than being plugged and abandoned. This could provide a relatively inexpensive monitoring network.

Possibly consideration could be given to retaining suspended oil wells in specified producing areas (deepest and most 'isolated') as potential "disposal fields" rather than requiring abandonment of the wells as is done presently. This would be conditional on the wells being "mechanically sound" so that they could be "moth-balled" until such time as they might be required for waste disposal. On the same basis, one or more of the suspended field wells could be used to monitor disposal operations, all at considerable cost saving.

An additional factor worthy of consideration could be (compulsory?) location of waste-generating facilities in the regions most suitable for subsurface disposal, provided surface environmental considerations also are favourable. This would do away with the danger and expense involved in surface transport of waste to an off-site disposal facility.

In conclusion, it must be stressed that this is not an in- depth study of all aspects of the potential for subsurface disposal of liquid industrial waste in Manitoba; it is a preliminary, and primarily geological study, intended to provide a reasonably comprehensive framework on which more detailed studies and evaluations can be based. In particular, detailed studies of reservoir hydrodynamics are required to determine rates of, and potential for, regional flow of formation fluids which would result in migration of a waste-disposal plume. Any such migration would almost certainly be towards the biosphere and hence of critical importance in any evaluation of disposal potential.

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