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**SUBSURFACE
WASTE-DISPOSAL POTENTIAL
OF SASKATCHEWAN**

by

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PROVINCE OF SASKATCHEWAN

PREFACE

By virtue of the multidisciplinary nature of the topic, this study was undertaken as a joint project under the auspices of the Saskatchewan Geological Survey Branch (F. Simpson) and the Petroleum and Natural Gas Administration Branch (E. G. Dennison).

ABSTRACT

Search objectives in evaluation of formations for deep-well disposal of industrial fluid wastes are hydraulically isolated units with good reservoir quality, abruptly terminated laterally as a result of lithologic variation of depositional or diagenetic origin and delimited vertically by impermeable strata. The normative subsurface-disposal condition of no hazard to population, accompanied by optimum allocation of drilling funds, is best achieved through search for primary and alternative disposal formations by evaluation of hydrogeologic data on a basin-wide scale in the light of experience gained from earlier fluid-injection practice. Although stratigraphic-trap configurations of strata are characteristic for the Phanerozoic succession of Saskatchewan, any decision to drill a disposal well in the area is made under considerable uncertainty, which is a reflection of the present reconnaissance level of subsurface information.

In the Williston basin region as a whole, subsurface disposal is largely confined to sandstone and carbonate aquifers (Cambrian through Lower Cretaceous) of the Saskatchewan-Manitoba tectonic shelf, which in the north is flanked by the igneous-metamorphic terrain of the Canadian Shield and in the south is replaced by the deeper basin proper. As of mid-1973, 30 industrial disposal wells had been drilled in Saskatchewan: 20 were in operation, 5 suspended and 5 abandoned. Up to the end of 1972, more than 118.995 million bbls of fluid wastes, exclusive of oilfield brines, had been injected into subsurface aquifers in Saskatchewan:

1. waste brines (63,440,000 bbls), resulting from shaft and solution mining, as well as experimental solution of Middle Devonian potash deposits;
2. waste brines (50,390,000 bbls), produced during solution mining of caverns in Devonian halite for subsequent storage of liquefied petroleum gases and dry natural gas;
3. refinery effluent (3,530,000 bbls), comprising sour water and spent caustic from 2 plants; and
4. brines containing small amounts of mercury compounds (221,000 bbls) from a chlor-alkali plant, associated with previously injected wastes (874,000 bbls) from production of the herbicides 2,4-D and MCPA.

Depths of injection intervals range from 1,448 to 4,692 feet. The maximum depth of a disposal well in Saskatchewan is 5,536 feet. Average injection rates are from 3 to 1,100 US g/m and average wellhead pressures vary from the sole influence of gravity to 1,750 psig. More than 44.13 per cent of all industrial wastes injected into the Saskatchewan subsurface are received by clastic aquifers. In 18 injection systems, clastic units (Cambrian and Ordovician; Lower Cretaceous) are the disposal intervals, while 13 wells have been completed for disposal into carbonate units (Silurian through Mississippian). There are 4 multizone completions, each involving disposal of potash brines into both a Silurian carbonate aquifer and an Ordovician clastic aquifer. In 3 disposal systems, mercury compounds are permitted to accumulate in the growing caverns of a brine field with production from Devonian evaporite strata.

Excellent Cambrian and Ordovician sandstone aquifers and Silurian carbonate aquifers currently receiving potash waste brines at depths in the range 3,670 to 4,692 feet are the deepest disposal units and though poorly known at present, they are likely to be of increasing importance to the potash industry in the future. Upper Devonian and Mississippian

carbonate formations are also used successfully at present for disposal of salt-cavern brines and refinery wastes. However, collapse structures and associated vertical fractures in these strata, above the sites of natural solution removal of Middle Devonian evaporite beds by formation waters, and cross-formational flow of ground water at the sub-Mesozoic unconformity may facilitate vertical migration of wastes to higher aquifers and should be taken into account during the search phase of decision making. Fluvatile and fluviomarine sand bodies of Early Cretaceous age constitute the shallowest disposal aquifers at present, with wastes of all main categories injected at depths in the range 1,600 to 2,690 feet. These and younger deposits are considered to be largely unsuitable for waste injection, because of close correspondence between the valley systems they occupy, the distribution of preglacial aquifers also of fluvatile origin and present-day drainage patterns, all controlled to a large extent by salt-solution phenomena.

Although improved technology might be reasonably expected to reduce the amounts of toxic refinery and chemical-plant wastes, injected into the Saskatchewan subsurface, deep-well disposal is the only currently viable alternative to surface storage of potash and salt-cavern brines in lagoons and natural depressions, which would occupy many acres of potential farmland and would also greatly increase the possible threat of contamination of ground water in near-surface, drift and bedrock aquifers.

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INTRODUCTION

THE PROBLEM

Ecological demand, defined in the *Study of Critical Environmental Problems* recently carried out under the auspices of the Massachusetts Institute of Technology (SCEP, 1970) as the "summation of all man's demands on the environment, such as the extraction of resources and return of wastes," tends to grow exponentially and is therefore in long-term perspective unsustainable (Forrester, 1971), chiefly because of the finite nature of non-renewable resources and the limited capacity of an industrialized ecosystem to withstand disruption through pollution. Increasing realization of the importance of this last-mentioned factor has led to two contrasting, though complementary goals in industrial waste management:

1. reduction of unwanted industrial output (energy and materials) through improvement in technology and recycling of wastes; and

2. innovation in waste-disposal technique to minimize pollution hazard by isolating wastes from the environment with increased efficiency. In recent years, attention has been focussed increasingly upon injection into deep subsurface aquifers as a means of attaining the latter aim with regard to liquid industrial wastes. In the Williston basin region of western Canada and the northern United States (Figs. 1 and 2), subsurface disposal of liquid industrial wastes is largely confined to the Saskatchewan portion of the relatively shallow tectonic shelf, which delimits the basin in the north and is itself replaced northward by the igneous-metamorphic terrain of the Canadian Shield. Since completion of Saskatchewan's first industrial disposal well in 1958, more than 118.995 million bbls of fluid wastes, exclusive of oil-field brines (Table 1), have been injected into subsurface aquifers in the province.

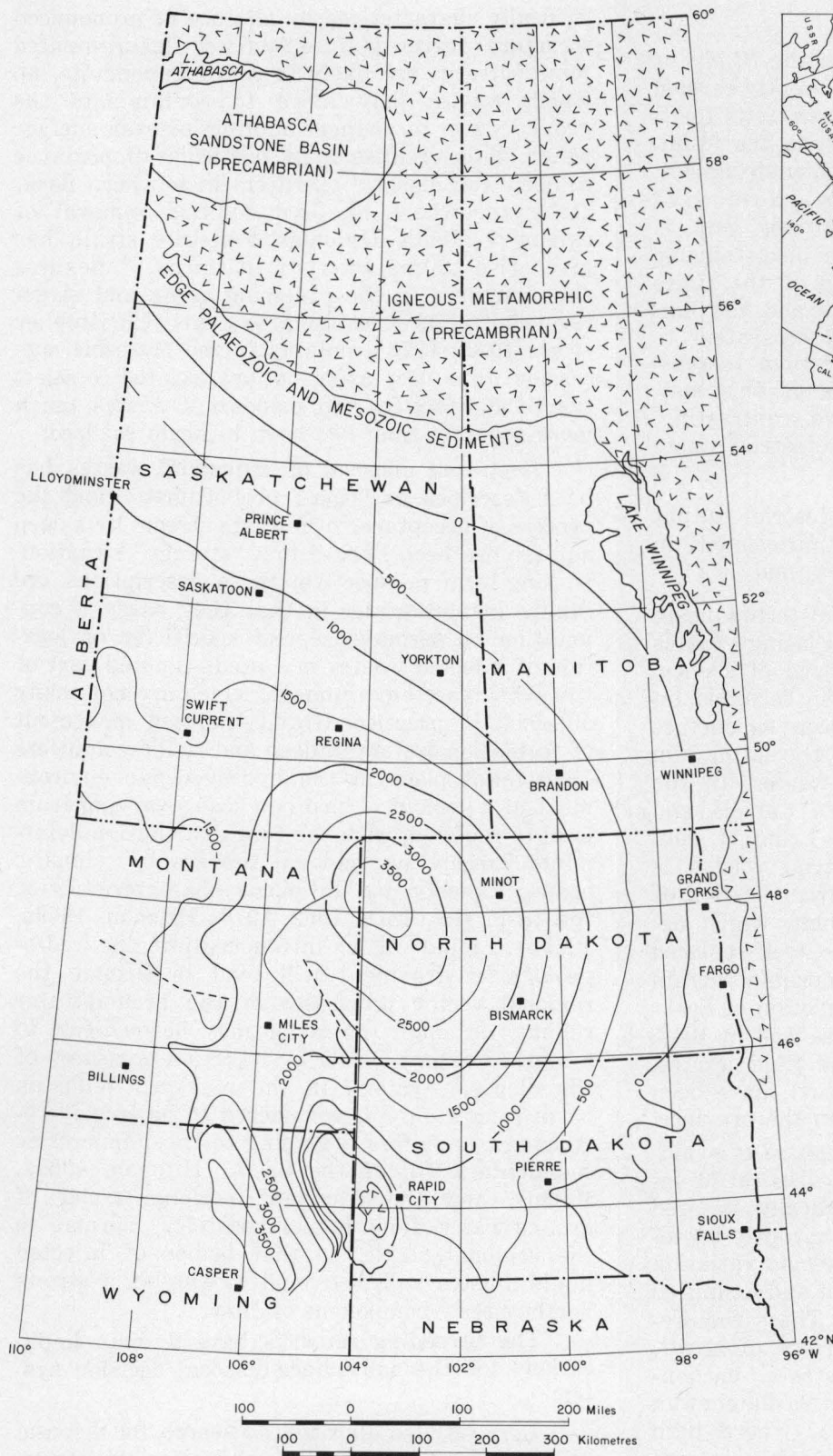
Drilling targets in the search phase of evaluation of formations for deep-well disposal of industrial fluid wastes are hydraulically isolated units with good reservoir quality, abruptly terminated laterally as a result of lithologic variation of depositional or diagenetic origin and delimited vertically by impermeable strata. These requirements are fulfilled in a wide variety of stratigraphic-trap configurations of strata, encountered in the subsurface of southern Saskatchewan (Christopher *et al.*, 1971; 1973), where both clastic and carbonate aquifers ranging in age from Upper Cambrian to Lower Cretaceous are used as repositories for liquid wastes. However, it should be noted that a deep-well disposal locale

is ideally characterized by absence of pronounced structural features, since faults or flexure-related joint patterns are likely to serve as conduits, up which wastes may move to contaminate the ground water of younger aquifers or even surface water. This premise is of particular importance to deep-well disposal operators in southern Saskatchewan, where localized solution removal of extensive Middle Devonian evaporite strata has given rise to characteristic patterns of flexures and fractures in the overlying rocks and structural control of depositional systems (Christopher *et al.*, 1971; 1973), notably in the Mesozoic succession, thus decreasing options, related to selection of aquifers for safe disposal of wastes, much more severely than has been hitherto realized.

Deep-well disposal of industrial wastes has been described as "final" or "ultimate" and the process of acceptance of a waste stream by a deep aquifer has been likened to a "storage" situation. In long-term perspective, these descriptions are highly inappropriate, in that they carry a connotation of permanence and specificity of location of injected wastes in a predesignated part of the subsurface environment, which are not easily obtained in practice. Gravity-induced movement of formation waters in deep and shallow aquifers alike takes place in the hydrogeologic environment of a geological basin on scales varying from local to regional, with the flow distribution determined largely by regional topography, climate, basin geometry and lithologic characteristics of the basin fill (Toth, 1962, 1970; Hitchon, 1969a, 1969b). Liquid wastes introduced into the hydrogeologic environment will tend to assume the regional vector properties of the ground-water regime, although the latter may be modified to a marked extent locally by injection pressures of the disposal system. In the northern Williston basin region, flow is considered to be largely restricted to aquifers belonging to the Phanerozoic sedimentary fill of the basin (Hitchon, 1969a, 1969b), and the dominant regional trend of ground-water flow is northeasterly, normal to the regional strike, so that bodies of injected liquid wastes will also tend to exhibit a strong northeasterly component of flow.

The preceding remarks have 2 main implications for the subsurface-disposal decision system:

1. A rational approach to search for disposal aquifers, based upon the application of stratigraphic-sedimentologic principles to reservoir engineering, is both feasible and indispensable for the safe operation of a disposal well.



LOCATION MAP

Contour interval: 500 metres or
500 x 3.3 feet.

Contours on Precambrian basement.
Negative elevations.

Datum: sea level.

Credit: King, P.B., 1969.

Fig. 1— Location map and structure contours on Precambrian surface, Williston basin proper and northern tectonic shelf, Saskatchewan, Manitoba, North Dakota, South Dakota and eastern Montana.

2. It is important to monitor deep-well disposal operation by means of observation wells drilled to the disposal aquifer, so that if necessary, steps may be taken to control the subsurface migration of injected waste.

PREVIOUS WORK

The first published account of subsurface disposal of liquid industrial wastes in Saskatchewan appeared in the inventory of information on North American disposal wells, compiled by the Interstate Oil Compact Commission (Ives and Eddy, 1968, pp. 36, 38, 56-57), and included an outline of information required of prospective deep-well disposal operators by the Department of Mineral Resources, as well as listings of some of the main characteristics of 4 disposal systems then in use. The disposal wells considered were: the refinery-waste disposal systems of Consumers' Cooperative Refineries Limited and Imperial Oil Limited, at Regina; the herbicide-waste disposal system of Interprovincial Cooperatives Limited (later to become Northern Industrial Chemicals Limited; now the Prince Albert Pulp Company) at Saskatoon; and a potash-brine disposal well of the International Minerals and Chemical Corporation of Canada at Esterhazy. These same injection systems are listed by van Everdingen and Freeze (1971, Table II, p. 32) as Saskatchewan's contribution to subsurface disposal of industrial wastes in Canada. However, by the end of 1971, disposal wells in Saskatchewan were numbering as many as 19, 2 of which were no longer in operation (Vonhof and van Everdingen, 1972). This dramatic increase came about by the addition of 5 new potash-brine disposal systems and 8 salt-cavern brine disposal systems. An interesting paper by de Korompay (1972) provided details of deep-well injection of brines in two of the new potash-brine disposal systems, namely those of Sylvite of Canada Division of Hudson Bay Mining and Smelting Co. Limited at Rocanville. The most recent survey of deep-well injection of industrial wastes in Saskatchewan was by Dennison and Simpson (1973), who gave information about 30 injection systems, of which 5 had been abandoned and 5 suspended. These are the injection systems considered in the present account (Table 2). Also of significance is a paper by Sandberg (1962) on the general geology of the neighbouring Williston basin proper, which provides a basis for considerations of subsurface disposal of radioactive wastes.

SCOPE OF STUDY

In this report, the hydrogeologic milieu of deep-well disposal of liquid industrial wastes in

Saskatchewan is described and industrial experience of waste injection in the province and neighbouring areas is summarized. Discussion of the possible environmental impact of existing subsurface-disposal systems, as well as the hydrogeologic and economic constraints on deep-well disposal of a variety of waste categories in Saskatchewan, determined largely by local peculiarities of stratigraphy and structure, is developed to provide guidelines for future disposal-well operators in the province.

The chapters, *Subsurface Waste-Disposal Systems in Saskatchewan* and *Economic Factors in Subsurface Waste Disposal*, are by both authors. The rest of the account is contributed by Simpson, who coordinated all the material and edited the first draft of the manuscript.

METHOD OF INVESTIGATION

The data on the waste-injection systems of Saskatchewan, presented in this report, came from non-confidential Saskatchewan Government files and from copies of a questionnaire, completed by representatives of companies engaged in deep-well disposal of wastes in the province. The questionnaire used in this study, titled *Questionnaire on Subsurface Waste-Disposal Operations in Saskatchewan* (Saskatchewan Department of Mineral Resources Form MR 508), was designed for the purpose of standardizing information on the subsurface waste-disposal decision system (Appendix I) and comprises a total of 40 questions, pertinent to the design and operation of a deep-well disposal facility and grouped into sections dealing with the following major topics:

1. the chemical and physical properties of injected wastes,
2. reasons for selection of the disposal site and the disposal formation,
3. drilling and completion of the injection well,
4. testing of the injection well and the disposal formation,
5. monitoring of deep-well disposal operations,
6. operational safeguards,
7. the economics of deep-well disposal compared with alternative methods of waste disposal, and
8. waste management considerations, including the desirability of legislation to control deep-well disposal and the need for relevant research.

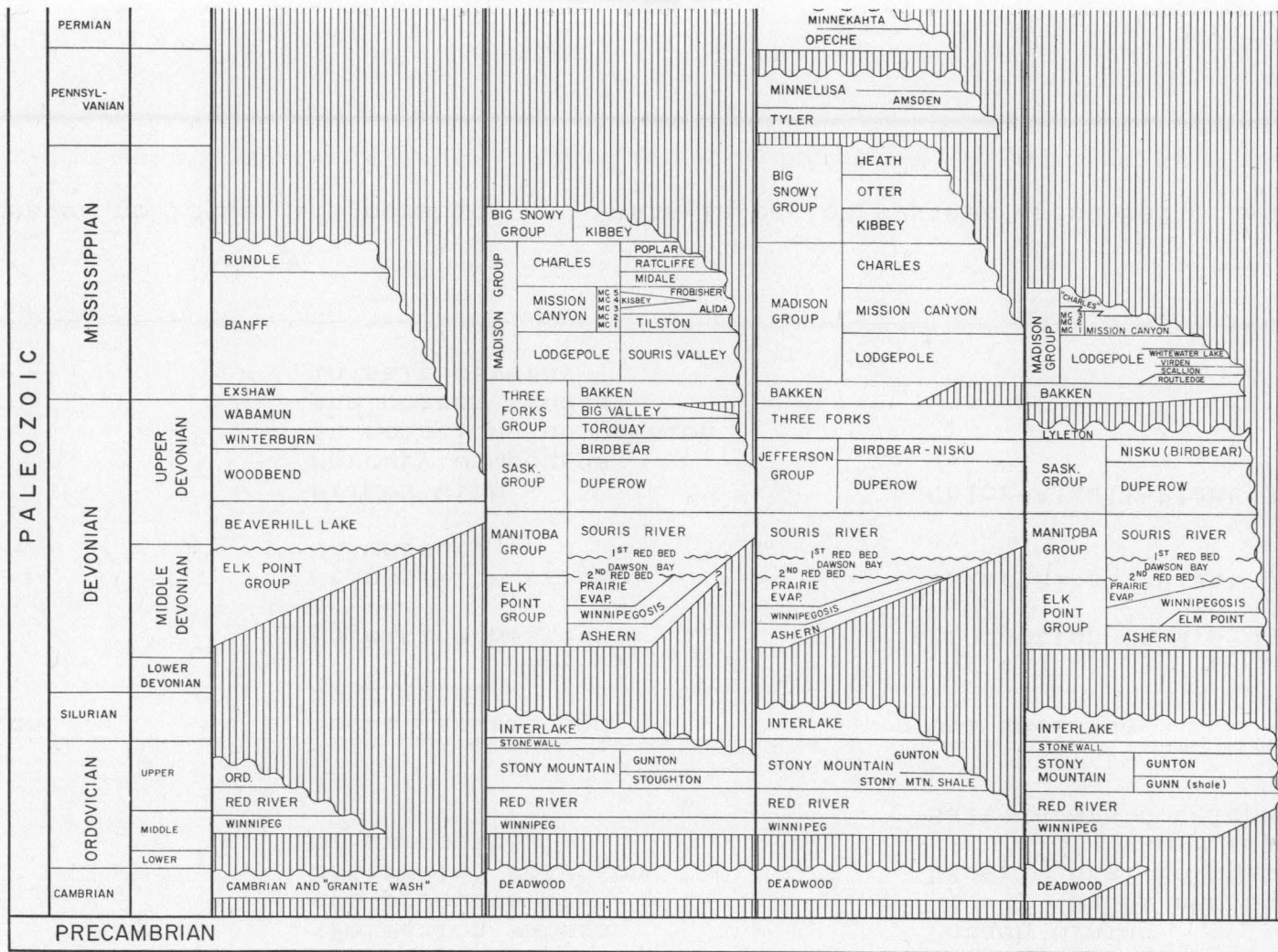


Fig. 2 — Stratigraphic correlation chart for the northern Williston basin region.

TABLE 1 - GENERALIZED CHARACTERISTICS OF WASTES INJECTED INTO SUBSURFACE STRATA,
NORTHERN WILLISTON BASIN REGION

GENERALIZED WASTE CATEGORY	NATURE OF WASTE	WASTE-FORMING INDUSTRIAL PROCESS
"Natural"	Brines (Formation waters and products of controlled solution of evaporites)	Oilfield Development Potash Mining (Shaft and Solution) Experimental Solution of Evaporites * Salt-Cavern Development
"Foreign"	Spent Caustic and Sour Water Herbicide Wastes * Brines with traces of mercury Brines with Mercury compounds in solution, suspension and bottom sludge in salt caverns	Oil Refining Production of 2,4-D and MCPA * Chlor-Alkali-Plant Operation Chlor-Alkali-Plant Operation

* Processes no longer in operation and waste-injection systems abandoned or suspended

TABLE 2 - OPERATIONAL STATUS OF SUBSURFACE WASTE-DISPOSAL SYSTEMS
 IN SASKATCHEWAN TO END OF YEAR 1973

OPERATIONAL STATUS	NUMBER OF WELLS	PERCENTAGE OF TOTAL WELLS
Injection not permitted	—	—
Failure (never operated)	—	—
Suspended	5	16.13
Abandoned	5	16.13
Operating	20	64.42
Pending	1	3.22
Total wells	31	100.00

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A copy of the questionnaire was mailed to each of the 14 companies operating disposal wells in the province, together with a letter outlining the nature of the study. The questionnaire also formed the basis for interviews of representatives of these companies during the winter months of 1972 to 1973. All questionnaires were completed and returned to the authors. Companies and local government authorities were also contacted for information on the status of deep-well disposal of wastes throughout the entire Williston basin region.

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Preparation of the report was greatly facilitated by full co-operation of all companies involved in subsurface waste-disposal operations in Saskatchewan. The authors acknowledge their indebtedness to these operators and in particular to the following individuals, who kindly supplied information on the deep-well disposal activities of their companies in Saskatchewan and adjacent areas: on potash-mine brine disposal — W. H. Eatock, A. E. Rodin and E. E. Kuntz (Allan Potash Mines, Allan); J. M. Gordon and K. J. Cahoun (Central Canada Potash Co. Limited, Colonsay); C. R. Haryett (Duval Corporation of Canada, Saskatoon); D. Mraz (International Minerals and Chemical Corporation (Canada) Limited, Esterhazy); R. A. G. Ursel (Kalium Chemicals Limited, Belle Plaine); and D. C. Smith and F. J. Greeves (Sylvite of Canada, Division of Hudson Bay Mining and Smelting Co., Limited, Rocanville); on salt-cavern brine disposal — R. R. Andrews, E. L. Forgues and H. Howard (Dome Petroleum Limited, Calgary); R. W. Ormiston (Pacific Petroleums Limited, Regina); D. C. Ruse (of Cavern Engineering Limited, Regina, and consultant for Procor Limited); and D. G. Olafson and R. Woof (Saskatchewan Power Corporation, Regina); on refinery-waste disposal — B. F. Dahlstrom (Consumers' Co-operative Refineries Limited, Regina); V. O. Juba and A. R. Pankiw (Husky Oil Operations Limited, Lloydminster); and R. B. Thomson, L. Krushelnitzky and E.

Ziobrowski (Imperial Oil Limited, Regina); and on other industrial waste-disposal — W. J. Rutledge (Domtar Chemicals Limited, Unity) and B. B. Bentley and L. Goodwin (Prince Albert Pulp Company, Saskatoon); D. C. Ruse (Cavern Engineering Limited, Regina) took part in discussions of the subsurface-disposal systems in Saskatchewan, with which his company has been associated.

W. M. Catterson (Shell Canada Limited, Toronto), J. D. Muir (Canadian Salt Company Limited, Montreal), J. D. Ross (Hooker Chemicals Canada Limited, Brandon) and D. C. Severs (Petroleum Association for Conservation of the Canadian Environment, Ottawa) also supplied useful information, pertinent to the aspect of environmental management under consideration. C. B. Folsom, Jr. (North Dakota Geological Survey, Grand Forks), H. D. Hadley (Montana Department of Natural Resources and Conservation, Billings), H. R. McCabe (Manitoba Department of Mines, Resources and Environmental Management, Winnipeg), D. J. McGregor (South Dakota Geological Survey, Vermillion) and R. O. van Everdingen (Inland Waters Directorate, Environment Canada, Calgary) provided Simpson with useful data on the status of subsurface waste disposal in neighbouring areas. In addition, Simpson gratefully acknowledges the help of K. H. Lanouette (Industrial Pollution Control, Inc., Westport, Connecticut), who provided information on the cost of removal of heavy metals from wastes; J. E. Christopher (Saskatchewan Department of Mineral Resources), E. R. Magathan (Union Oil Company of Canada Limited, Calgary), A. E. Stevens (Department of Energy, Mines and Resources, Ottawa) and J. A. Vonhof (Inland Waters Directorate, Environment Canada, Calgary), who each discussed the results of highly relevant geological research prior to its publication; T. S. Tamaki (Saskatchewan Department of Mineral Resources), who kindly discussed legal aspects of harm from pollution; T. W. Rey and D. F. Bowhay (Ground Water Division, Saskatchewan Department of the Environment), who supplied information on municipal use of ground water from Saskatchewan bedrock aquifers; and D. G. Smith (Saskatchewan Department of Mineral Resources), who gave details of experimental work on solution of potash ore and related deep-well disposal. F. Waldie (Saskatchewan Government Systems Center) wrote the computer program used in the project for retrieval of a listing of wells with core- and water-analysis data. The figures were drafted by R. P. Kydd, J. Beerkens and J. Bedo.

A RATIONAL APPROACH TO DECISION MAKING IN UNDERGROUND WASTE MANAGEMENT

GENERAL STATEMENT

The methodology of decision analysis can be a significant aid to public decision makers, concerned with waste-disposal problems, and in particular those involved with subsurface-disposal decision systems, since rigorous, step-by-step analysis minimizes the danger of sub-optimization, that is, temporary solution of a disposal problem through creation of a long-term pollution problem. The main stages of decision analysis, arising in evaluation of legislation against air pollution (Ellis and Keeney, 1972), have general application to anti-pollution legislation and are here rephrased to relate to subsurface disposal of industrial wastes:

1. structuring the decision problem by (a) formulation of the problem, (b) identification of objectives, and (c) selection of measures of effectiveness;
2. describing possible consequences of alternative disposal programs in terms of the effectiveness measures;
3. prescribing relative preferences of the decision maker for each possible consequence, that is, precise identification of trade-offs between conflicting objectives; and
4. rationally synthesizing information from stages 1 to 3 above, to select a disposal program.

In industrial waste-disposal situations, the problem involves determination of the merits of alternative modes of disposal and evaluation of various disposal formations, if deep-well injection is one of the disposal methods under consideration. A generalized objective, assumed to be desirable to both industry and local government, is that of maintaining high environmental quality; but conflicting sub-objectives arise, where trade-offs must be made between reduction of disposal-system costs and minimization of adverse effects upon health and economy. Measures of effectiveness may be determined only through consideration of the output sector of the model for evaluation of waste-disposal legislation (Fig. 3).

Discussion of the possible output of deep-well injection in turn requires detailed consideration of the hydrogeologic setting of the proposed disposal system. Furthermore, adequate determination of the effectiveness of measures taken may be made only when the subsurface behaviour

of a waste stream has been ascertained and this can only be done by means of observation wells drilled to disposal formations. In the industrialized ecosystem designed and managed by man (Koenig and Tummala, 1972; Koenig *et al.*; 1972), monitoring of waste-disposal operations is an essential function of environmental engineering.

NORMATIVE SUBSURFACE WASTE DISPOSAL

Search objectives in petroleum-exploration strategy and disposal-formation evaluation alike are stratigraphic units of good reservoir quality, containing commercial accumulations of hydrocarbons in the former and with potential to become repositories of fluid wastes in the latter. Both types of subsurface search activity are high-risk ventures, but failure in the disposal situation can be much more costly than mere loss of investment capital for the well drilled, and in the worst instance may entail civil liability for harm from pollution. Furthermore, the profit motive of the petroleum-exploration decision system is replaced in the waste-injection decision system by the goal of optimization of drilling, testing and well-completion techniques, so that minimum well costs are incurred with no hazard to population. This normative subsurface waste-disposal condition can be best achieved through systematic search for primary and alternative disposal aquifers, by evaluation of hydrogeologic data on a basin-wide scale in the light of experience gained from current disposal practice. Hydrogeologic information prerequisite to the normative disposal condition includes data on:

1. porosity-permeability gradients of potential disposal aquifers, as well as variation of any incorporated reservoir heterogeneities and the confining aquitards;
2. compatibility of a given waste type with the lithologies of potential disposal aquifers and their pore fluids;
3. structural setting and patterns of subsurface movement of formation fluids.

Decisions as to primary and alternative target aquifers permit consideration of drilling optimization as a function of bit selection, mud program, hydraulic factors (flow rate and pump pressure), weight on the bit and rotary speed, and the most favourable completion technique can be finalized. Though the waste-injection decision

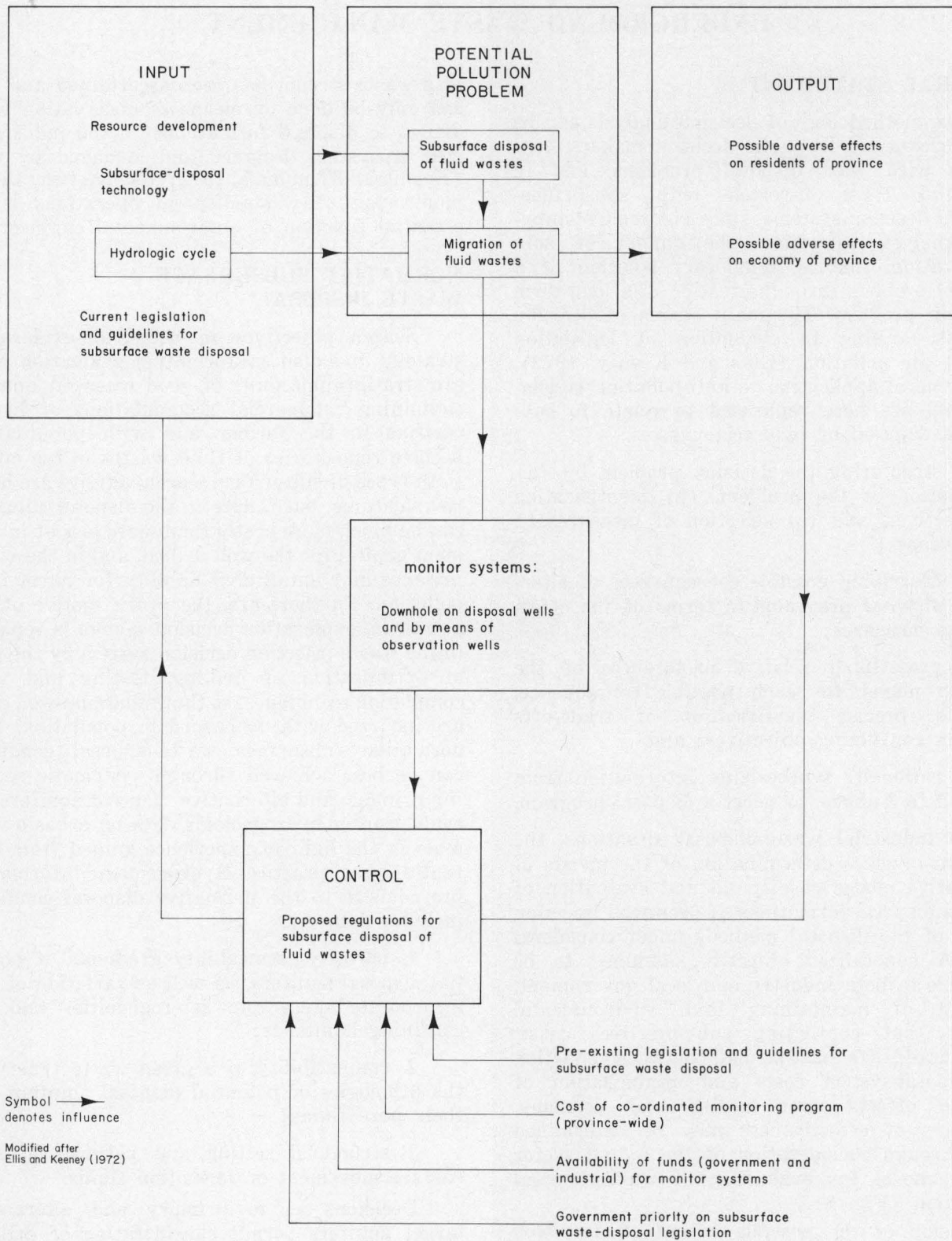


Fig. 3 — General model for evaluation of regulations controlling subsurface disposal of fluid wastes.

system is only a minor part of the total corporate decision system, it will undoubtedly gain in importance during years to come, as a result of mounting public concern over environmental matters.

At present, there is no specific legislation for deep-well injection of industrial wastes in Saskatchewan and all waste disposal into subsurface aquifers is regulated in accordance with The Oil and Gas Conservation Act of 1969. Administration of the regulatory Act is by the Department of Mineral Resources. Civil liability for harm from pollution in Saskatchewan is determined on the basis of tort-law theories arising out of English common law; and also certain statutory laws administered by the Saskatchewan Department of the Environment.

OUTLINE OF SUBSURFACE DISPOSAL IN SASKATCHEWAN

As of mid-1973, 30 industrial disposal wells had been drilled in Saskatchewan: 20 were in operation, 5 suspended and 5 abandoned. Up to the end of 1972, more than 118.995 million barrels of fluid wastes, exclusive of oilfield brines, had been injected into the subsurface strata of Saskatchewan:

1. waste brines (63,440,000 bbls), resulting from shaft and solution mining, as well as experimental solution of Devonian potash deposits;
2. waste brines (50,930,000 bbls), produced during solution mining of caverns in Devonian halite for subsequent storage of liquefied petroleum gases and dry natural gas;
3. refinery effluent (3,530,000 bbls), comprising sour water and spent caustic from 2 plants; and
4. brines containing small amounts of mercury compounds (221,000 bbls) from a chlor-alkali plant, associated with previously injected wastes (874,000 bbls) from the production of herbicides.

The distribution of subsurface waste-disposal systems in Saskatchewan and Manitoba is shown in Figure 4. When oil-field brine injection is taken into account, the amount of fluid waste injected into subsurface aquifers is seen to exceed 2.599 billion barrels.

The depths of injection intervals range from 1,448 to 4,692 feet. The maximum depth of a disposal well in Saskatchewan is 5,536 feet. Average injection rates are from 3 to 1,100 US g/m and average well-head pressures vary from the sole influence of gravity to 1,750 psig. More than 44.13 per cent of all industrial wastes

injected into the Saskatchewan subsurface are received by clastic units. In 18 injection systems, clastic units (Cambrian and Ordovician; Lower Cretaceous) are the disposal intervals, while 13 wells have been completed for disposal into carbonate units (Silurian to Mississippian). There are 4 multizone completions, each involving disposal of potash brines into a Silurian carbonate unit and an Ordovician clastic unit. In 3 disposal systems, mercury compounds are permitted to accumulate in caverns in Devonian evaporite strata.

GEOLOGICAL SETTING

The geology of the northern Williston basin region has been summarized by Christopher *et al.* (1971, 1973), who emphasized reservoir quality and gross geometry of lithologic units in their considerations of hydrocarbon potential. Some additional material, dealing mainly with outcrops is presented in Simpson (1973). The outline of geology, relevant to subsurface waste disposal given in the present account, is largely based on these syntheses. Discussions of the chemistry of formation waters are based on Porter and Fuller (1959), Bannatyne (1960) and Hitchon (1964).

Topographically, the sedimentary region of Saskatchewan and Manitoba is divided into three steppes by eastward-facing scarps, the Manitoba Escarpment in western Manitoba and the Missouri Coteau of southern Saskatchewan. The prevailing slope is to the east and elevations are mostly in the range of 700 to 2,000 feet above sea level; the maximum elevation is 4,567 feet in the Cypress Hills of Saskatchewan. A poorly drained, forested belt, of low but variable relief, extends parallel to the sedimentary edge and within this area scattered exposures of Mesozoic and Palaeozoic rocks are found. Flat plains and undulating topography predominate farther south, their continuity interrupted only by broad river valleys and a few areas of positive relief, where exposures of Upper Cretaceous and younger sediments may occur. The information content of the outcrops is low and detailed knowledge of the stratigraphy is derived from some 20,000 wells, drilled during exploration for petroleum, natural gas and potash.

Strata with waste-disposal potential in southern Saskatchewan and southwestern Manitoba account for 71.9 per cent (220,000 square miles) of the area, but only 38.5 per cent (330,000 cubic miles) of the sedimentary volume in the Williston basin region (Fig. 1), which also includes eastern Montana, western North Dakota and northwestern South Dakota. They constitute a predominantly (95 per cent) marine, sedi-

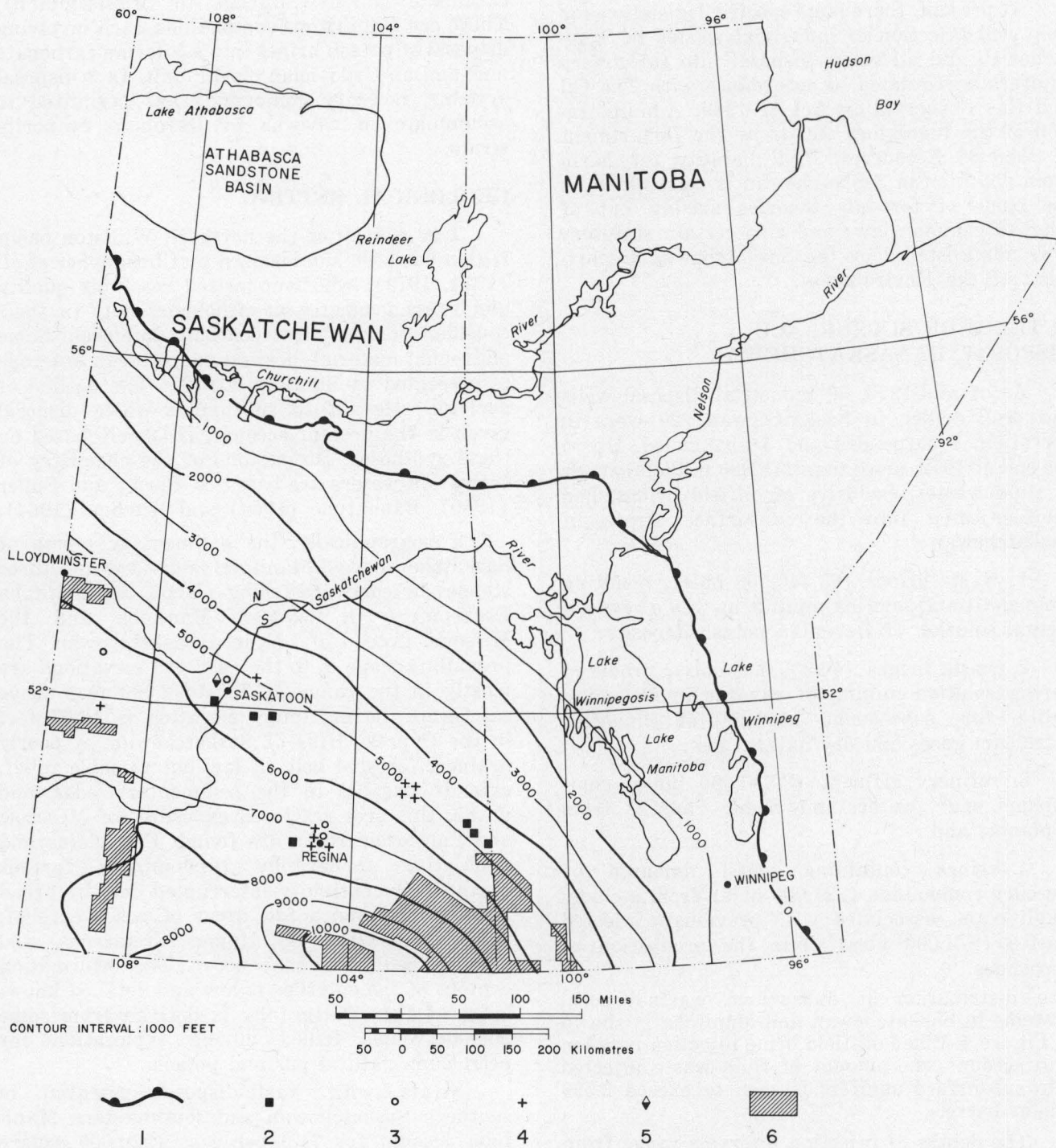


Fig. 4 — Distribution of subsurface waste-disposal systems on isopach map of Phanerozoic sequence, Saskatchewan and Manitoba.

1—southern perimeter of Precambrian Shield
 2—potash brine injection
 3—refinery and chemical-plant waste injection

4—salt-cavern brine injection
 5—chemical-plant waste disposal in salt caverns
 6—oilfield brine injection

mentary prism, which defines a stable tectonic shelf throughout most of the Canadian part of the Williston basin region, bounded to the north by Precambrian rocks of the Canadian Shield and replaced southward by the northern margin of the basin proper. The principal stratigraphic units of the northern Williston basin region are shown in Table 1. In general, the sediments dip up to 50 feet per mile in a predominantly south-westerly direction. They thicken in excess of 10,500 feet in southeastern Saskatchewan, and 16,700 feet in the deepest part of the basin proper of North Dakota. The succession consists of three principal divisions, delimited by major unconformities and exhibiting important differences in both gross lithology and incorporated mineral resources:

1. a lowermost clastic division (Middle to Upper Cambrian; Middle Ordovician) up to 1,600 feet in thickness and with production of helium and nitrogen in southwestern Saskatchewan;

2. a middle carbonate-evaporite division (Middle Ordovician to Mississippian) of maximum thickness 4,800 feet, yielding light and medium oil in southeastern Saskatchewan, heavy oil in west-central Saskatchewan, and potash and sodium chloride in central Saskatchewan; and

3. an upper clastic division (Triassic to Holocene) reaching 5,300 feet in thickness, with production of light, medium and heavy oils and natural gas in western Saskatchewan as well as extensive lignite deposits and a wide variety of industrial minerals, including sodium sulphate, silica sands, clays and marls at locations throughout southern Saskatchewan.

Formation fluids of great economic importance are proven commercial quantities of hydrocarbons, restricted to a southeastern district of Mississippian oil reservoirs and a western district with five main production trends comprising Mississippian Jurassic and Cretaceous oil and Cretaceous non-associated gas reservoirs. Total dissolved solids and chloride content of formation waters exhibit variation, which is facies- and structure-dependent, and also show increases with age and depth. High chloride content of formation waters in the lower and middle divisions is localized in the west and southeast; the western belt assumes greater importance for formation waters of the upper division.

UNCERTAINTY IN WASTE-INJECTION DECISION SYSTEMS

Any decision to drill a disposal well in Saskatchewan is made under considerable uncertainty, which is a reflection of the reconnaissance level

of subsurface information throughout the province as a whole. Of great importance to all subsurface search activities of private companies in Saskatchewan are:

1. the series of detailed geological reports, maps, charts and statistical publications, obtainable from the Department of Mineral Resources;

2. ready access to well information through the Provincial Government's computerized data storage and retrieval system, recently described by Buller (1972);

3. the comprehensive inventory of well samples and cores, which may be examined at the Subsurface Geological Laboratory in Regina.

Trends in quality and distribution of subsurface information in Saskatchewan (Christopher *et al.*, 1971; Simpson, 1972), relevant to search programs, directed toward potential disposal aquifers, are as follows:

1. High drilling densities are largely confined to clusters of wells forming the oilfields and subordinately the sites of potash production. Outside of the few townships, which constitute these production locales, well control for stratigraphic analysis is variable, though for the most part considerably reduced.

2. Petroleum exploration strategy has been aimed at specific stratigraphic units, usually the known producing formations. Thus, it is likely that with increased drilling in the province, the inventory of formations yielding commercial quantities of hydrocarbons will be expanded, particularly through discoveries in the basal clastic division and lower part of the carbonate-evaporite division.

3. Successively deeper formations are penetrated by progressively fewer wells to the extent that even in the townships of high drilling density, formations below the Devonian potash-rich unit (Prairie Evaporite) are poorly known. The upper clastic division is penetrated by all wells, whereas Mississippian, Devonian and Silurian formations are penetrated by 56.4 per cent, 12.4 per cent and 2.5 per cent of the wells respectively. Only 1.5 per cent of the wells reach the lower clastic division and no more than 0.7 per cent was drilled to basement.

4. Drill stem tests, core analyses and water analyses, to a large extent have been concentrated in potential pay zones near or within production locales. Similar data for the deep aquifers of greatest waste-disposal potential are scarce.

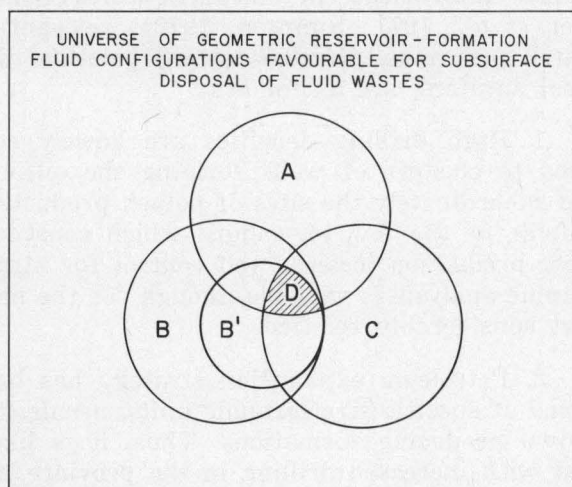
Thus, multiple conflicting objectives, costs and benefits accruing to various interest groups and consequences for environmental management, possibly extending far into the future, all

intrinsic to the subsurface waste-disposal decision system, arise in uncertainty situations, characterized by paucity of hydrogeologic data.

HYDROGEOLOGY

GENERAL STATEMENT

The oil and gas pools of Saskatchewan, reflect dominance of the stratigraphic trap (Christopher *et al.*, 1971; 1973). Comparable reservoir geometries in absence of hydrocarbons could provide adequate subsurface space for disposal of fluid wastes (Fig. 5) and in this setting, essentially similar rationales characterize the search phases of both petroleum-exploration



- A - FAVOURABLE DEPOSITIONAL GEOMETRY OF RESERVOIR
- B - FAVOURABLE HYDRODYNAMIC REGIME
- B' - FAVOURABLE HYDRODYNAMIC REGIME (NON-COMMERCIAL FORMATION FLUIDS)
- C - FAVOURABLE STRUCTURAL SETTING
- D - DISPOSAL AQUIFER CONDITION

Fig. 5—Venn diagram to show geometric reservoir-formation fluid configurations, favourable for subsurface waste disposal, and the disposal aquifer condition.

and fluid-injection decision systems. Although the general geology of the province, viewed in terms of distribution of the relatively flat-lying, principal stratigraphic units, is deceptively uncomplicated, stratigraphic analysis in areas of close well control reveals lateral facies change, reflecting differences in depositional environment, and structures, evidencing both Laramide rejuvenation of basement monadnocks and collapse of strata, attendant upon solution removal of the Middle Devonian Prairie Evaporite. Knowledge of these structural-stratigraphic idiosyncrasies of the cratonic setting and their possible implications for migration of fluids, injected

under high pressure, is of vital importance to subsurface waste-disposal operators, if widespread, irreversible contamination of groundwater is to be avoided.

BASEMENT RELIEF

The Precambrian erosion surface is composed of the following:

1. a homocline, defined by a generalized dip of 11 to 20 feet per mile, with the strike changing from northwesterly to northerly across Saskatchewan into Manitoba;

2. steepening of the dip to as much as 50 feet per mile in the southeast on the site of the ancestral Williston basin proper (Fig. 1);

3. the northwest-plunging Sweetgrass arch and south-plunging North Battleford arch, near the intersection of the Fourth Meridian and latitude 52 degrees (Fig. 6);

4. the prominent lineaments, which are the Meadow Lake escarpment of west-central Saskatchewan and the Nelson River feature of eastern Saskatchewan and Manitoba;

5. local domal features and monadnocks, which originated as a result of Laramide movements or were rejuvenated by these movements; Upward movement of positive basement features during deposition of the Phanerozoic sequence led to folding of the sediments, as well as localization of vertical fluid migration up associated fractures (Wilson *et al.*, 1963), giving rise to solution of the Prairie Evaporite and collapse of the overlying strata.

SALT-SOLUTION COLLAPSE FEATURES

Solution removal of salt from the Prairie Evaporite and concomitant collapse of younger strata have produced many structural features in southern Saskatchewan (Fig. 7). The largest of these is a roughly triangular, salt-free depression in southwestern and central-southern Saskatchewan, approximately 23,000 square miles in area and delimited by a prominent scarp in the northwest and northeast, where younger strata are draped over the present salt edge. Other local

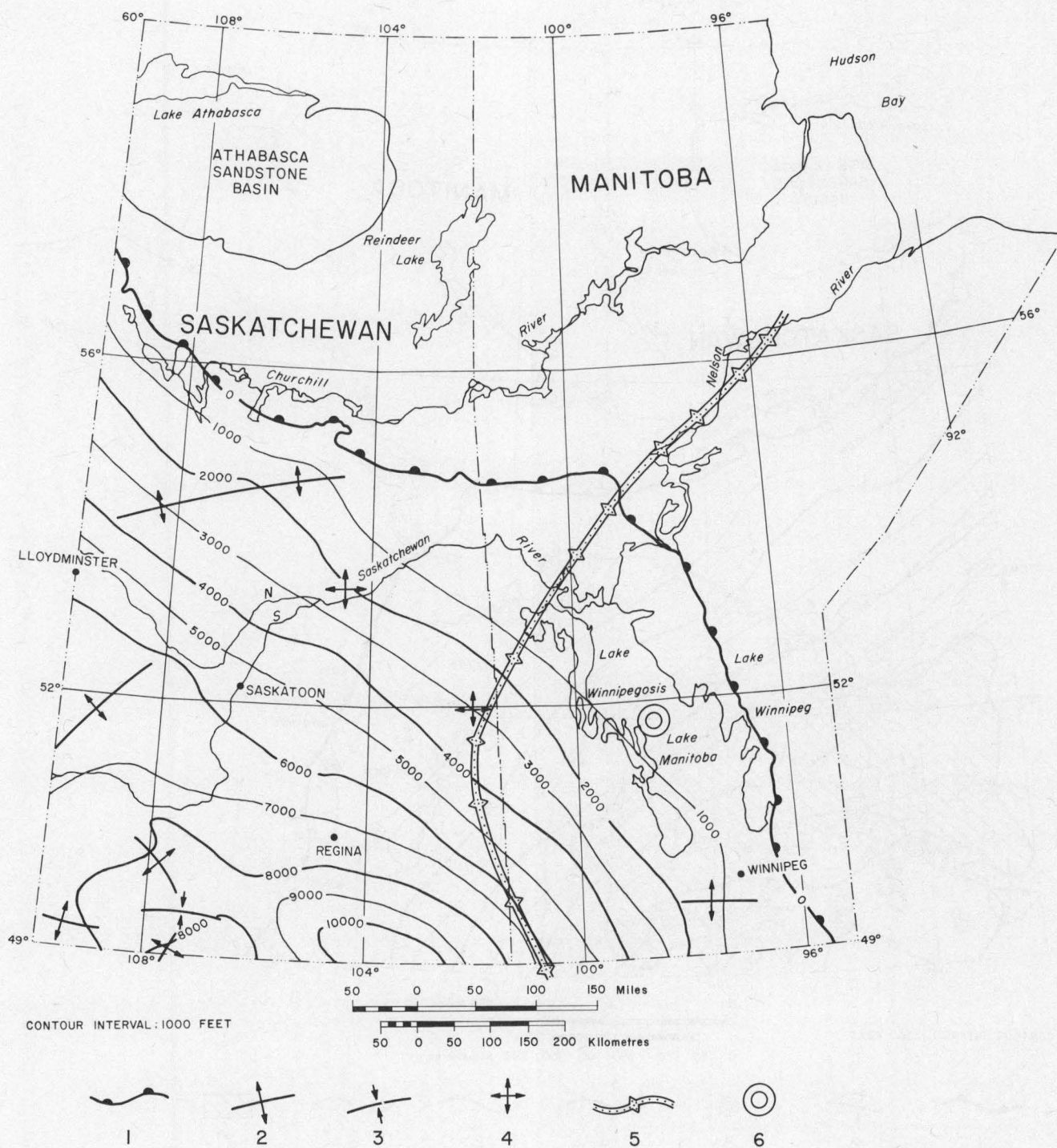


Fig. 6—Structural features of Precambrian basement with isopachs of Phanerozoic sequence superimposed, Saskatchewan and Manitoba.

- 1—southern perimeter of Precambrian Shield
- 2—positive feature
- 3—negative feature

- 4—local positive gravity anomaly
- 5—Nelson River gravity high
- 6—Lake St. Martin structure

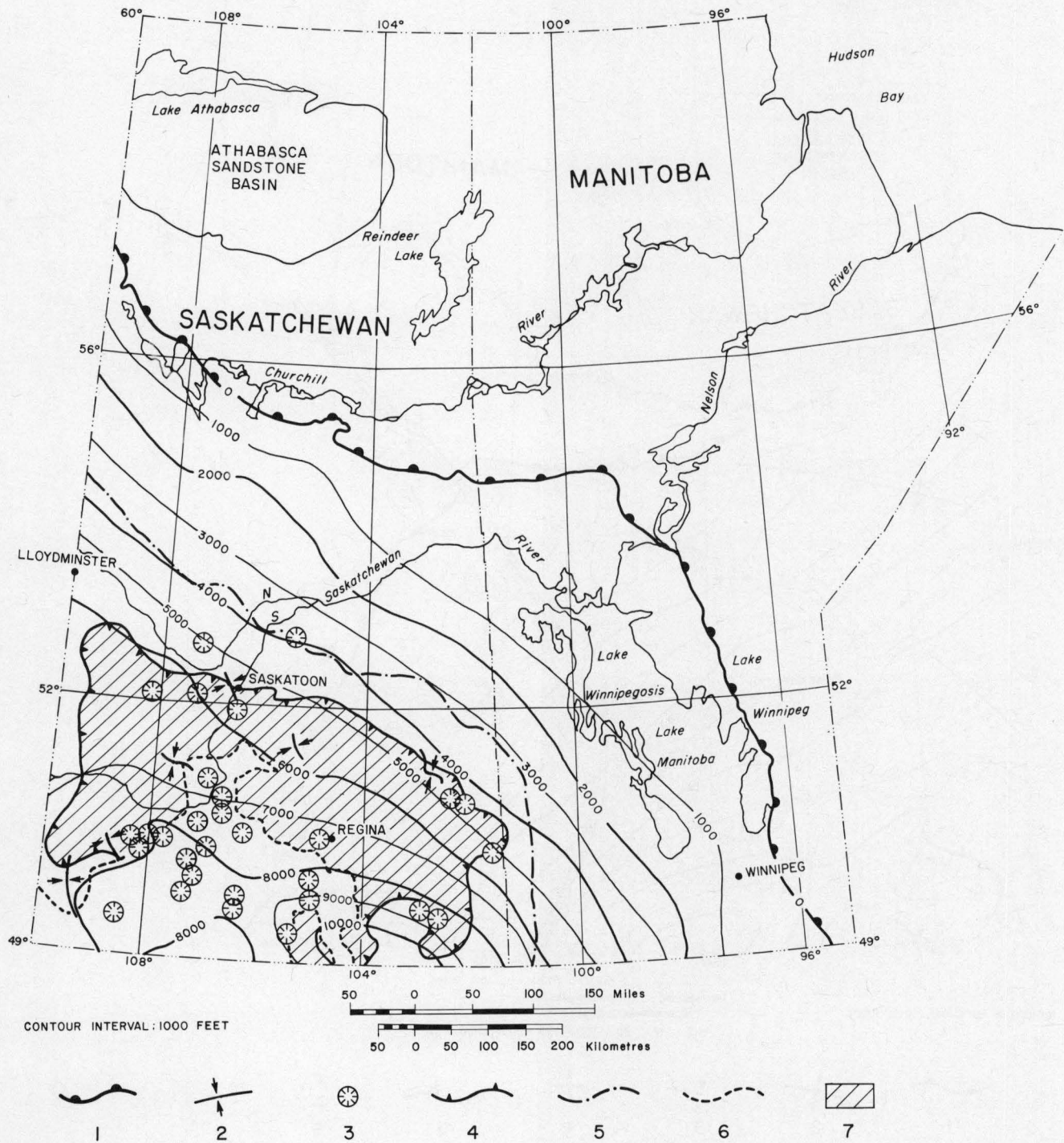


Fig. 7—Distribution of salt-solution and large-scale, circular structures, Saskatchewan and Manitoba.

- 1—southern perimeter of Precambrian Shield
- 2—linear solution features
- 3—sinks and large scale, circular structures
- 4—limit of soluble potassium minerals

- 5—limit of salt
- 6—area where Prairie Evaporite absent
- 7—area of potash production potential

and regional salt-solution structures are narrow, elongate troughs and smaller-scale, sub-circular, often fracture-bounded depressions. On the basis of isopach and structure-contour data on post-Prairie units, Kent (1968) provided an excellent review and analysis of evidence for accelerated solution removal of salt during several discrete intervals from the Late Middle Devonian to Late Cretaceous or Early Tertiary time, with the earliest solution events restricted to local channels, which subsequently coalesced to give the present edge of the Prairie Evaporite.

The relationship between positive features of the Precambrian erosion surface and overlying salt-solution phenomena was already noted. Instances of localization of solution removal of salt above anomalously thick Winnipegosis sections have also been described (Bishop, 1953). It is thought that Winnipegosis carbonate mounds constituted structurally high aquifers below the Prairie Evaporite and that solution took place along fractures in the salt, formed as a result of compaction above these elevations (Holter, 1969).

Linear solution depressions exerted a strong influence on development of fluvial channel networks, incised into the Devonian, Mississippian and Jurassic rocks appearing in order of decreasing age southward at the pre-Cretaceous unconformity, as well as the arrangement of succeeding fluvial and fluviomarine channel sands of the Mannville Group (Christopher, 1974). Mannville palaeotopographic features are mimicked by overlying structures in the younger, marine Cretaceous deposits and correspond closely with pre-glacial channels cut into the Cretaceous bedrock surface, the distribution of drift aquifer sands and patterns of present-day drainage. A linear depression in the Saskatoon district, described by Christiansen (1967), illustrates these points. Complex, intercutting relationships between Mannville channel-fill sandstones, close correspondence between these networks and younger fluvial systems, water pressures adequate to permit artesian flow and vertical fractures associated with salt-solution features render the Mannville succession largely unsuitable for injection of fluid wastes at the present reconnaissance level of subsurface information.

CRUSTAL INSTABILITY

Recent tectonic activity, as indicated by records of earthquakes in the Williston basin region, is summarized in Table 3.

The most recent seismic event, the epicentre of which was located at Bengough, Saskatchewan, in July, 1972, has been discussed by Horner *et al.*

(1973), who consider that Love- and Rayleigh-wave radiation patterns are indicative of a vertical strike-slip fault of strike N 30° E. The seismic events listed in Table 3 are of low magnitude, but similar earthquakes might be extremely damaging in a subsurface setting, in the vicinity of potash-mining operations, underground gas-storage systems or disposal wells (Simpson and Lennox, 1974). There is no record of major, industry-induced, crustal instability in Saskatchewan.

THE BASAL CLASTIC DIVISION

The basal clastic sequence (Fig. 8) consists of sandstones and shales, belonging to the Middle to Upper Cambrian Deadwood Formation and the Middle Ordovician Winnipeg Formation. These marine formations are separated by an unconformity in a narrow belt, extending from the Meadow Lake escarpment in central Saskatchewan to southwestern Manitoba. East of this belt, Middle Ordovician clastic rocks rest upon the Precambrian basement. These sediments are exposed in east-central Saskatchewan and central Manitoba, where 10 to almost 100 feet of the Winnipeg Formation constitute the entire basal clastic sequence.

The Deadwood Formation consists of coarse-grained, quartzose, glauconitic sand, replaced upward by calcareous siltstones and micaceous shales with intercalated, very fine-grained sandstones. Fine- to coarse-grained, poorly indurated, quartzose sands are succeeded by green shales in the Winnipeg Formation of Saskatchewan, whereas in southern Manitoba the unit as a whole is characterized by an upward coarsening from basal shales.

The highest salinities of formation waters (greater than 189,800 mg/l chloride) are encountered in the Williston basin proper (Porter and Fuller, 1959; Hitchon, 1964), surrounded by an area of less saline waters (94,900 to 189,000 mg/l chloride), which in turn is interrupted across central-southern Saskatchewan by a northeast-trending corridor of formation waters with low chloride content (less than 94,900 mg/l, as shown in Figure 9).

Waste brines from potash mining operations are injected into aquifers of the basal clastic division in four systems in southeastern Saskatchewan (multizone injection into Interlake carbonates and Winnipeg sandstones) and in three systems in the Saskatoon district (Deadwood Formation). The main restriction on disposal is imposed by the increase in reservoir heterogeneities as argillaceous intercalations and

TABLE 3 - RECENT TECTONIC ACTIVITY AS INDICATED BY EARTHQUAKES
RECORDED IN THE WILLISTON BASIN REGION TO END OF YEAR 1972

DATE OF SEISMIC EVENT	EPICENTRE LOCATION	MAXIMUM INTENSITY (EPICENTRE)	MAGNITUDE	RADIUS OF PERCEPTIBILITY (km.)
1. 15 May, 1909	S. Sask./N.W. N.D./N.E. Mon	VI	5.5 (approx.)	550
2. 8 Jul., 1968	Huff, N.D.	IV	4.4	50
3. 11 Oct., 1968	Bengough, Sask.	— 1	2.9	— 1
4. 26 Jul., 1972	Bengough, Sask.	IV	3.7	30

1 Effects apparently not felt at surface

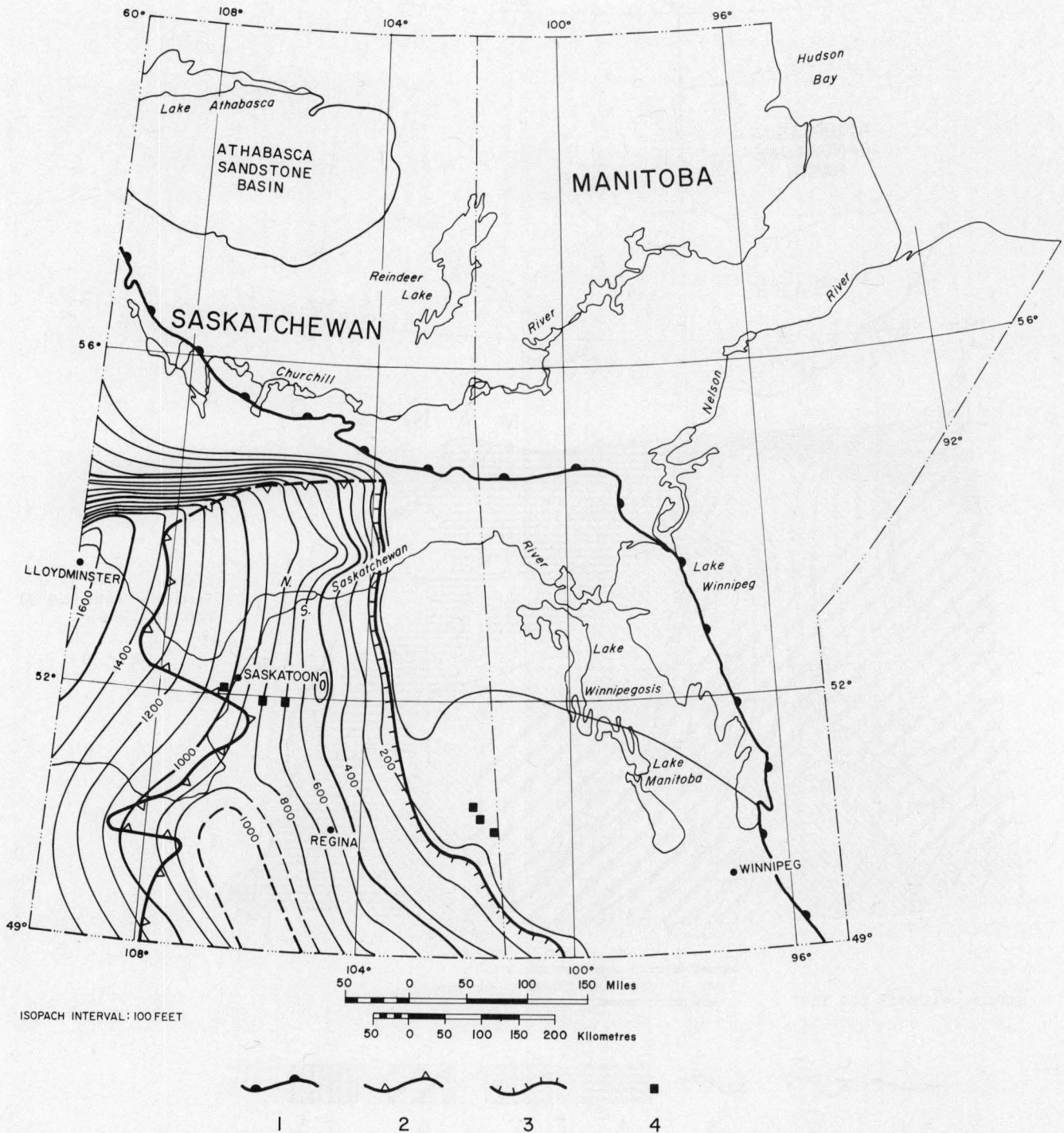


Fig. 8—The basal clastic division in Saskatchewan and Manitoba: Isopachs and distribution of sub-surface waste-disposal systems.

1—southern perimeter of Precambrian Shield
 2—limit of Winnipeg Formation

3—limit of Deadwood Formation
 4—potash brine injection

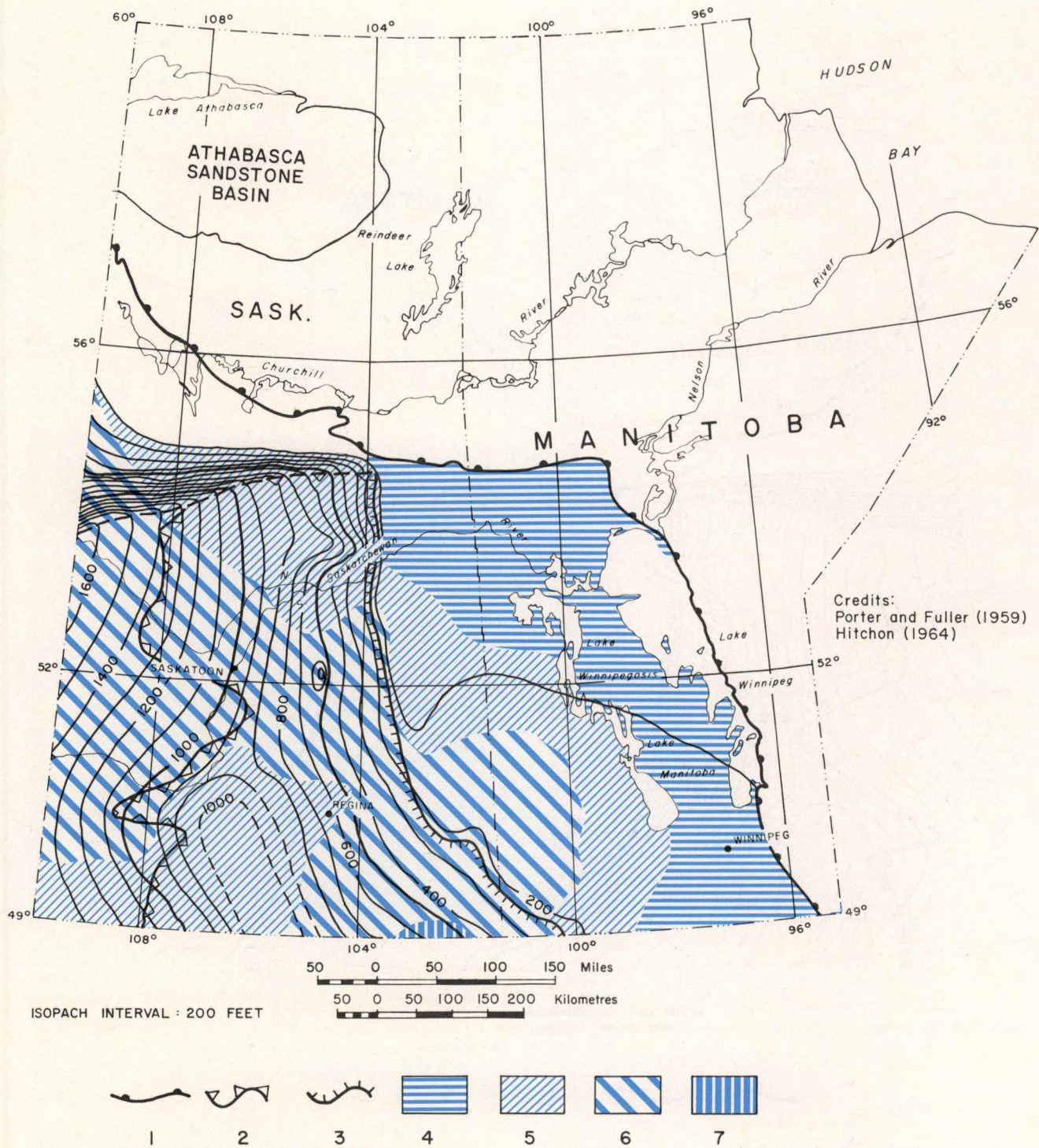


Fig. 9 — Chloride content of formation waters and isopachs of the basal clastic division in Saskatchewan and Manitoba.

- 1 — southern perimeter of Precambrian Shield
- 2 — limit of Winnipeg Formation
- 3 — limit of Deadwood Formation
- 4 — <18,980 mg/l

- 5 — 18,900-94,900 mg/l
- 6 — 94,900-189,800 mg/l
- 7 — >189,800 mg/l

corresponding loss of reservoir quality westward in the Deadwood Formation and southeastward in the Winnipeg Formation.

THE CARBONATE-EVAPORITE DIVISION

The carbonate-evaporite division (Fig. 10) overlies the Winnipeg Formation in central and eastern Saskatchewan and southern Manitoba, overlapping the Precambrian basement in central Manitoba and central Saskatchewan and Cambrian rocks of the basal clastic division in western Saskatchewan. The sequence forms a truncated wedge, of maximum thickness 4,800 feet in southeastern Saskatchewan and with a minimum thickness 250 feet in central Saskatchewan. These rocks reflect sedimentation in a variety of carbonate depositional environments, with vertical continuity of the carbonates interrupted by marker beds with relatively high argillaceous or arenaceous content and by generally thin evaporite beds, mainly of anhydrite, but with halite becoming important in Middle and Upper Devonian and Mississippian units. The thickest evaporite deposit (up to 600 feet) is the Middle Devonian Prairie Evaporite, made up of halite, sylvite, sylvinite and carnallite and occurring across central Saskatchewan and western Manitoba.

The pre- and early post-Prairie formations (Figs. 11 and 12) are characterized by southeastern and western areas of high salinity (94,900 to 189,800 mg/l chloride), separated in each case by a northeasterly corridor of relatively fresh water (less than 94,900 mg/l chloride). Hydrologic continuity across the sub-Devonian unconformity is indicated by the similarity between salinity distributions in Elk Point sediments and immediately underlying strata (Hitchon, 1964). The corridor (Figs. 11 and 12) coincides with a northeast-trending positive feature of the Lower Palaeozoic surface and also with the "salt-free" area of central-southern and southwestern Saskatchewan (Porter and Fuller, 1959; Christopher, 1961). Milner (1956) reports hydrodynamic evidence for northeastward movement of water, accompanied by solution of salt beds belonging to the Prairie Evaporite. Fluid migration in this direction has been demonstrated in the Interlake Group of the Regina district by Wilson *et al.*, (1963). Both Upper Devonian and Mississippian units (Figs. 13 and 14) exhibit high chloride content of formation waters in southeastern Saskatchewan (greater than 132,860 mg/l and 94,900 mg/l respectively), with values of less than 18,980 mg/l characteristic throughout the

remainder of southern Saskatchewan (Hitchon, 1964), suggesting general updip flow of brines from the Williston basin proper.

The carbonate-evaporite division receives waste and non-waste fluids representing all the major fluid categories injected into the Saskatchewan subsurface (Fig. 10). Injection of oil-field brines is largely restricted to the Mississippian oil producing units of the southeast. Of the potash brine disposal systems, 4 are associated with shaft mines and involve injection well below the Prairie Evaporite into the Silurian Interlake Group, whereas 1 in vicinity of a solution-mining operation has injection into Mississippian Souris Valley carbonates. One abandoned potash brine disposal well injected into the Upper Devonian Birdbear Formation. The Souris Valley Formation is the disposal unit in 4 salt-cavern brine disposal systems and 1 refinery-waste disposal system. The Duperow Formation receives "natural" brines from 1 salt-cavern brine disposal system and from the Domtar salt plant's disposal system. Accumulations of mercury compounds in three salt caverns in the Prairie Evaporite of the Saskatoon district provide the only instances of disposal of waste into halite in the province.

THE UPPER CLASTIC DIVISION

Triassic-Jurassic, Cretaceous, Tertiary and Pleistocene clastic sediments form the third division (Fig. 15), which unconformably overlies the carbonate-evaporite sequence in southern Saskatchewan and southwestern Manitoba and laps on to the Precambrian basement in central Saskatchewan. Terrestrial Triassic-Jurassic red, argillaceous sandstones, succeeded by marine red beds of anhydrite and dolomite and white dolomitic limestones, form the basal deposits. These are overlain by Middle Jurassic grey marine shales, sandstones and carbonates, which are followed in vertical succession by Upper Jurassic marine shales and sandstones. Lacustrine-fluviatile, fluviomarine and marine sandstones and shales of the Mannville Group (basal Cretaceous) rest unconformably upon Jurassic, Mississippian and Devonian strata in order of appearance northward. These deposits are overlain by Cretaceous marine shales, incorporating two main northeastward-thinning, regressive-transgressive wedges of conglomerates, diamictites, sandstones and intercalated mudstones. The older of these clastic wedges is the Bow Island-Viking sequence of the Colorado Group; the younger is the Belly River succession of the Montana Group. Continental environments of

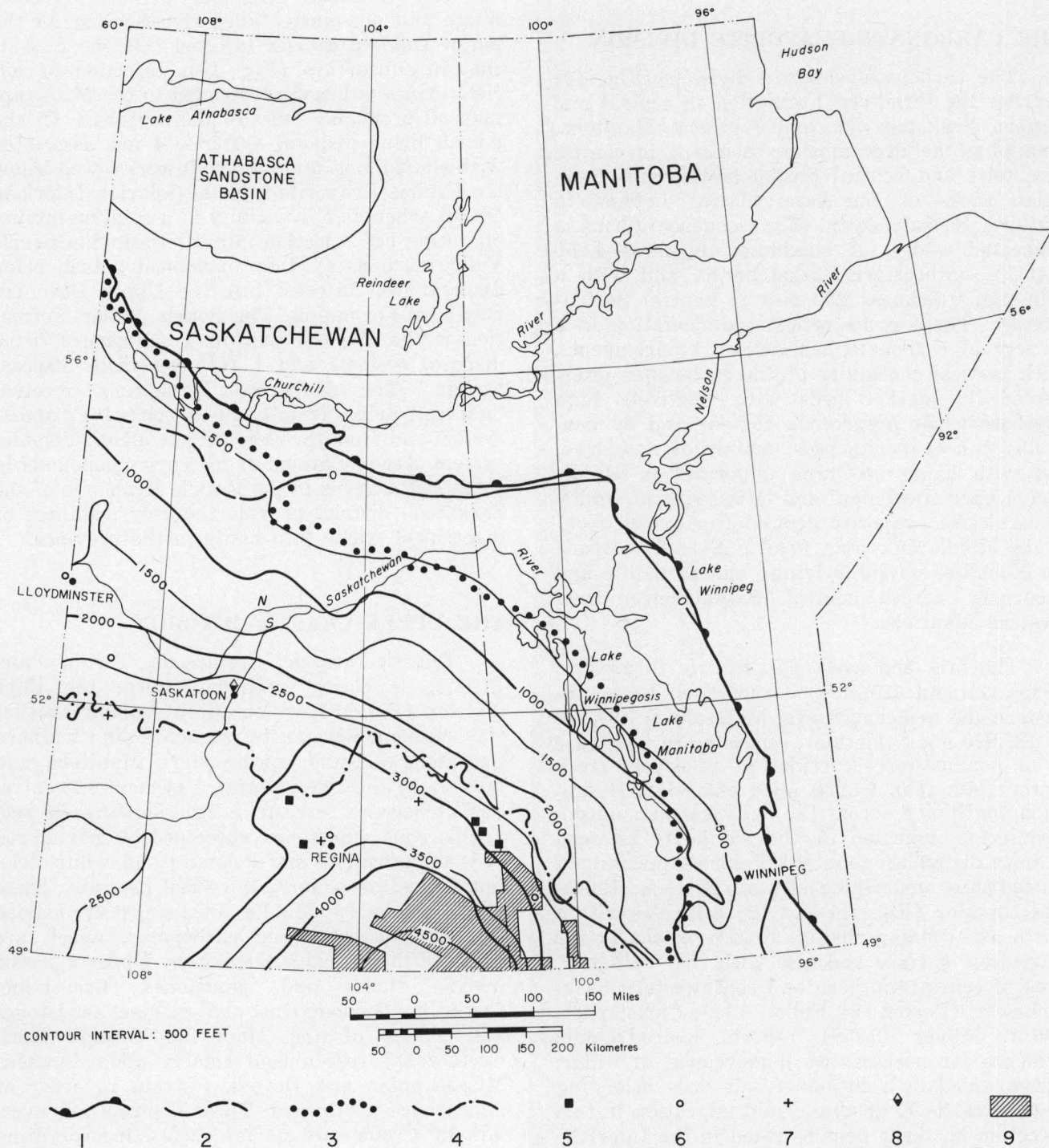


Fig. 10 — The carbonate-evaporite division in Saskatchewan and Manitoba: Isopachs and distribution of subsurface waste-disposal systems.

- 1— southern perimeter of Precambrian Shield
- 2— limit of Lower Palaeozoic rocks
- 3— limit of Devonian rocks
- 4— limit of Mississippian rocks
- 5— potash brine injection

- 6— refinery and chemical-plant waste injection
- 7— salt-cavern brine injection
- 8— chemical-plant waste disposal into salt caverns
- 9— oilfield brine injection

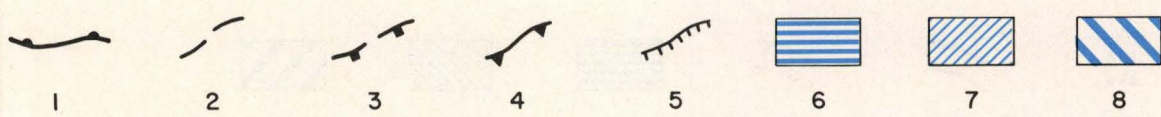
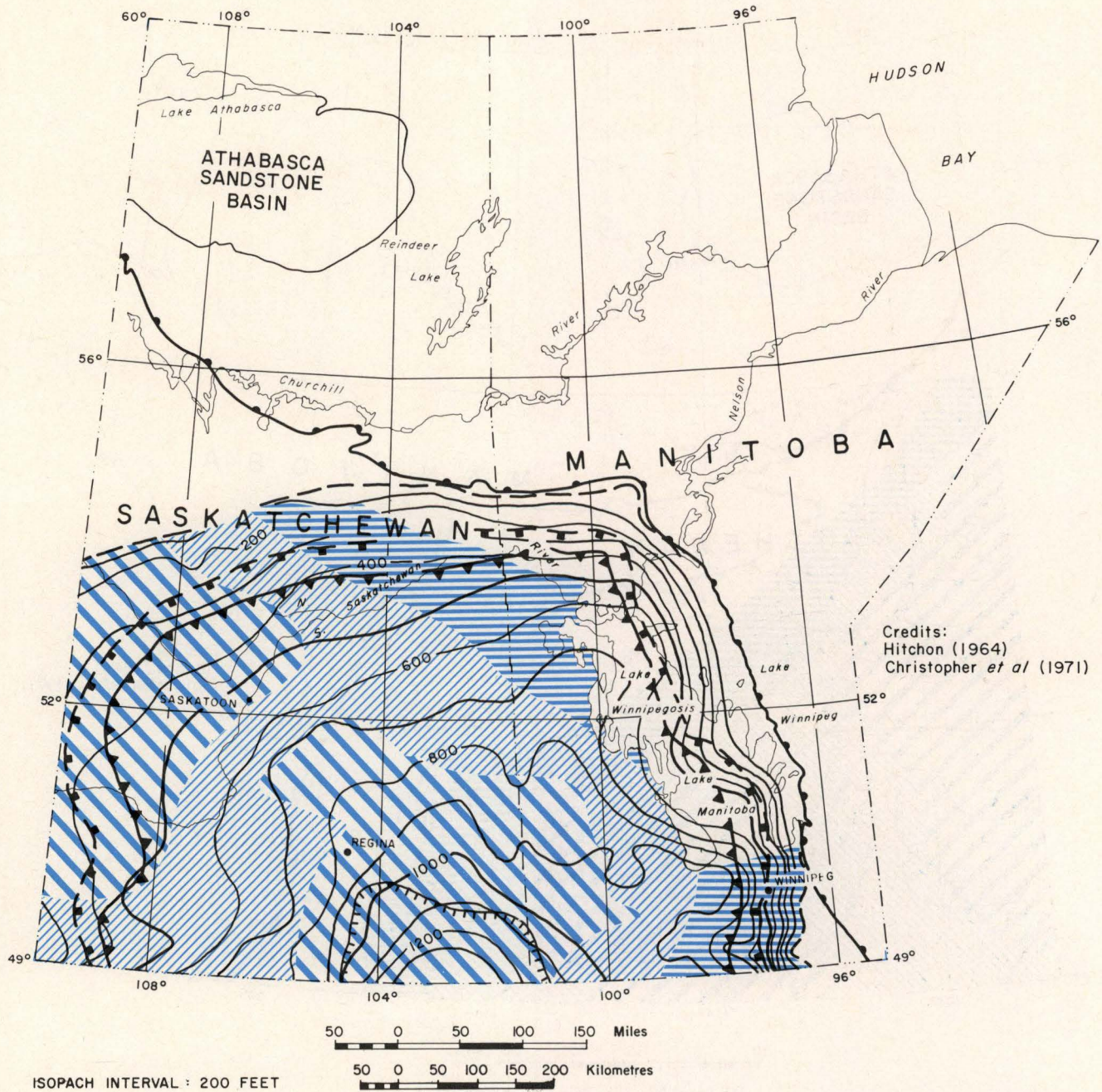
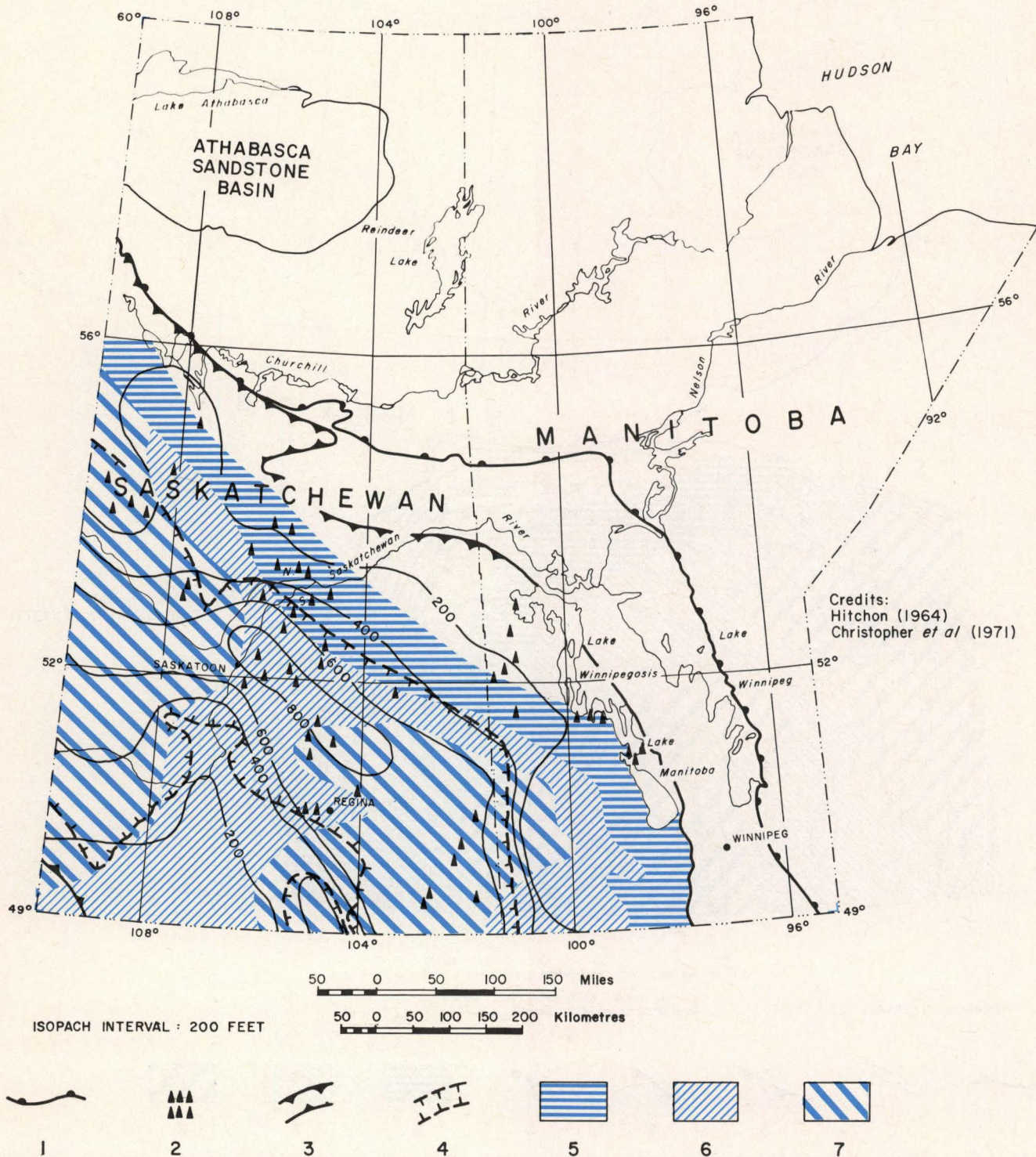


Fig. 11—Chloride content of formation waters and isopachs of units belonging to the carbonate-evaporite division in Saskatchewan and Manitoba: Lower Palaeozoic carbonate strata.

- | | |
|--|----------------------------|
| 1—southern perimeter of Precambrian Shield | 5—limit of Upper Interlake |
| 2—limit of Ordovician carbonate rocks | 6— <18,980 mg/l |
| 3—limit of Lower Interlake | 7—18,980-94,900 mg/l |
| 4—limit of Middle Interlake | 8—94,900-189,800 mg/l |



Credits:
Hitchon (1964)
Christopher *et al* (1971)

Fig. 12 — Chloride content of formation waters and isopachs of units belonging to the carbonate-evaporite division in Saskatchewan and Manitoba: Middle Devonian strata.

- | | |
|--|--|
| 1 — southern perimeter of Precambrian Shield | 5 — <math>< 18,980 \text{ mg/l}</math> |
| 2 — carbonate mounds | 6 — 18,980-94,900 mg/l |
| 3 — limit of Elk Point sediments | 7 — 94,900-189,800 mg/l |
| 4 — limit of Prairie Evaporite | |

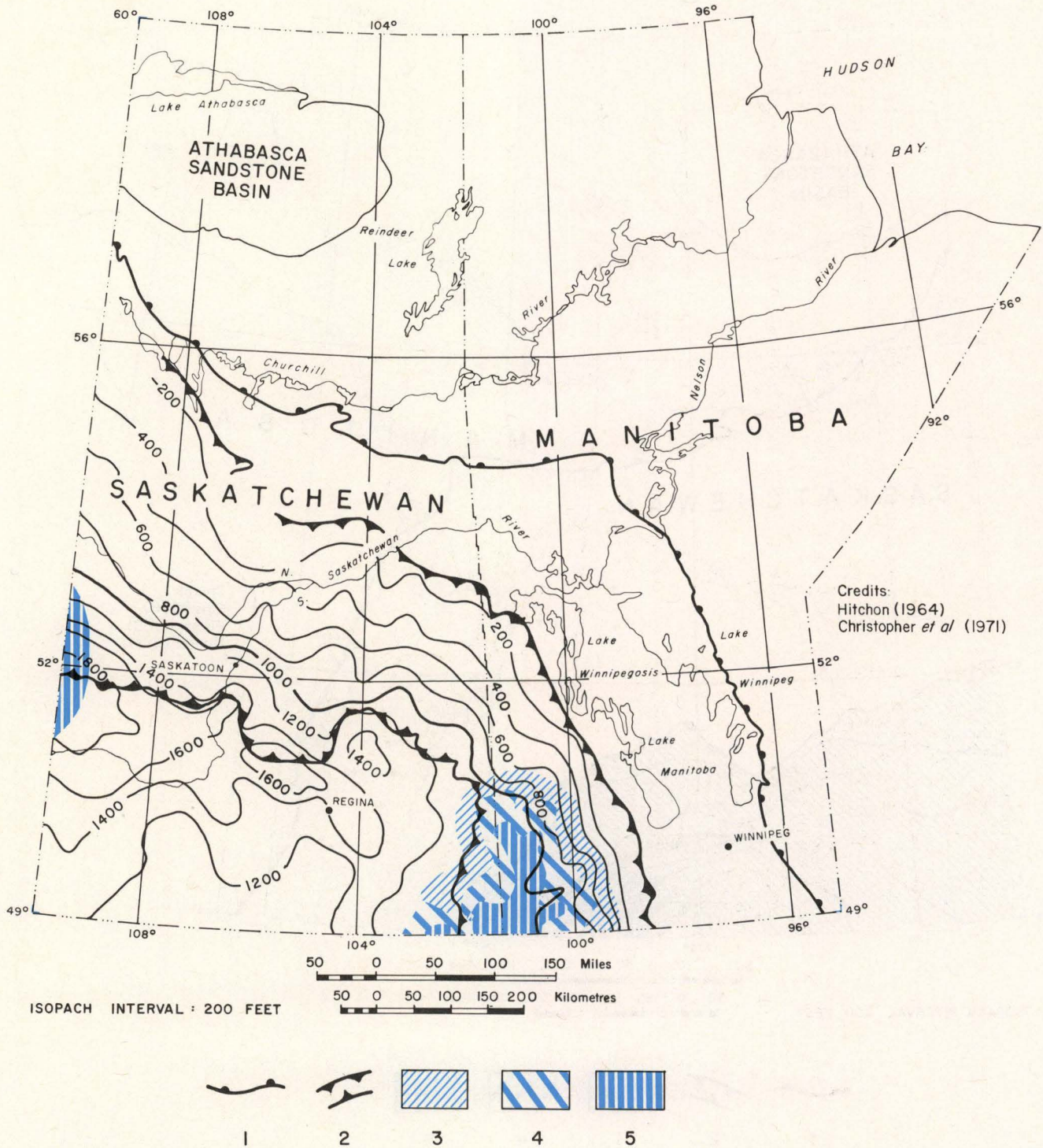


Fig. 13 — Chloride content of formation waters and isopachs of units belonging to the carbonate evaporite division in Saskatchewan and Manitoba: Upper Devonian strata.

- 1—southern perimeter of Precambrian Shield
- 2—limits of sub-cropping Upper Devonian rocks
- 3—<18,980 mg/l

- 4— 18,980-132,860 mg/l
- 5—>132,860 mg/l

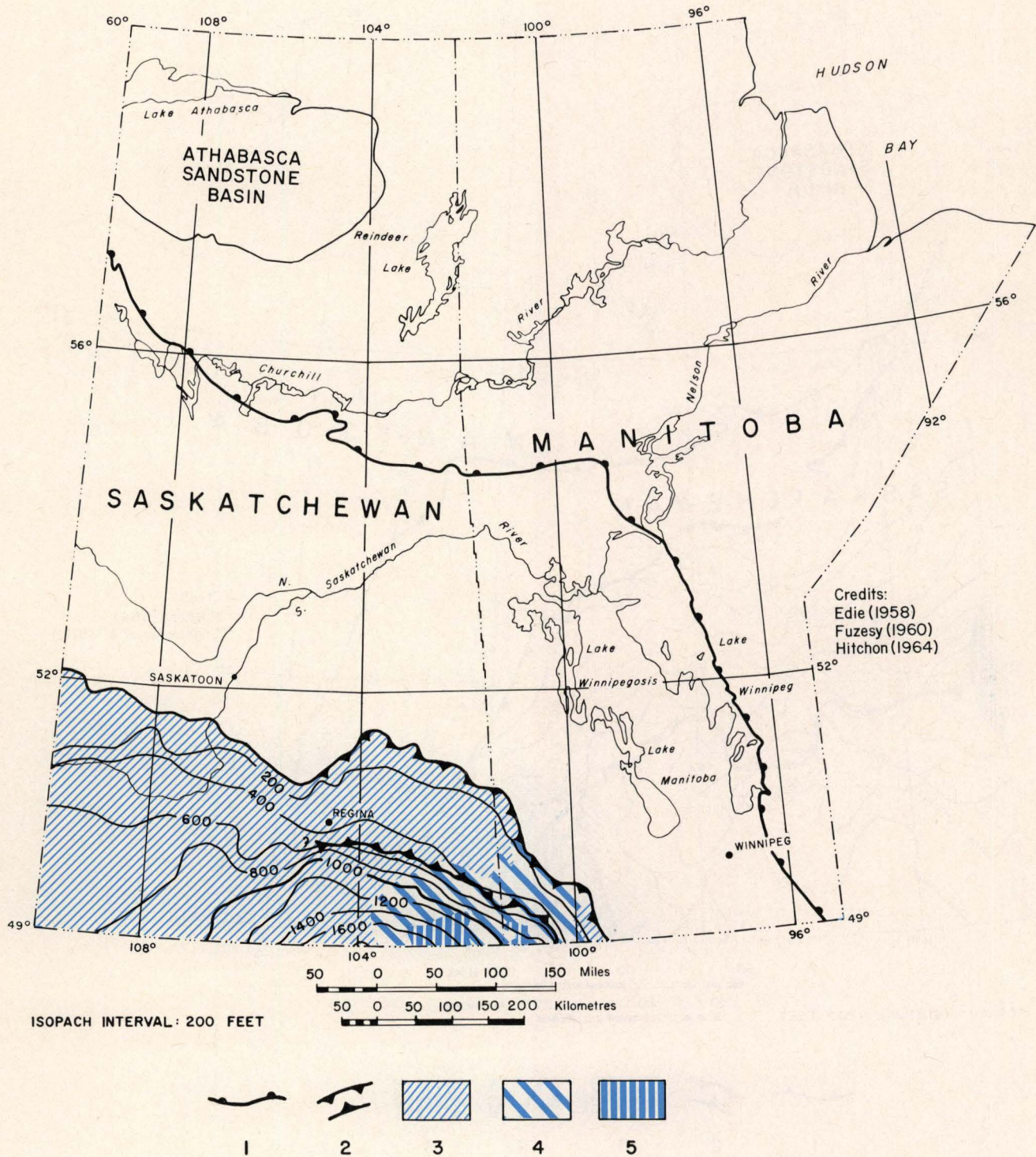


Fig. 14 — Chloride content of formation waters and isopachs of units belonging to the carbonate evaporite division in Saskatchewan and Manitoba: Mississippian strata.

- 1— southern perimeter of Precambrian Shield
- 2— limits of sub-cropping Souris Valley rocks
- 3— < 18,980 mg/l

- 4— 18,980-94,900 mg/l
- 5— > 94,900 mg/l

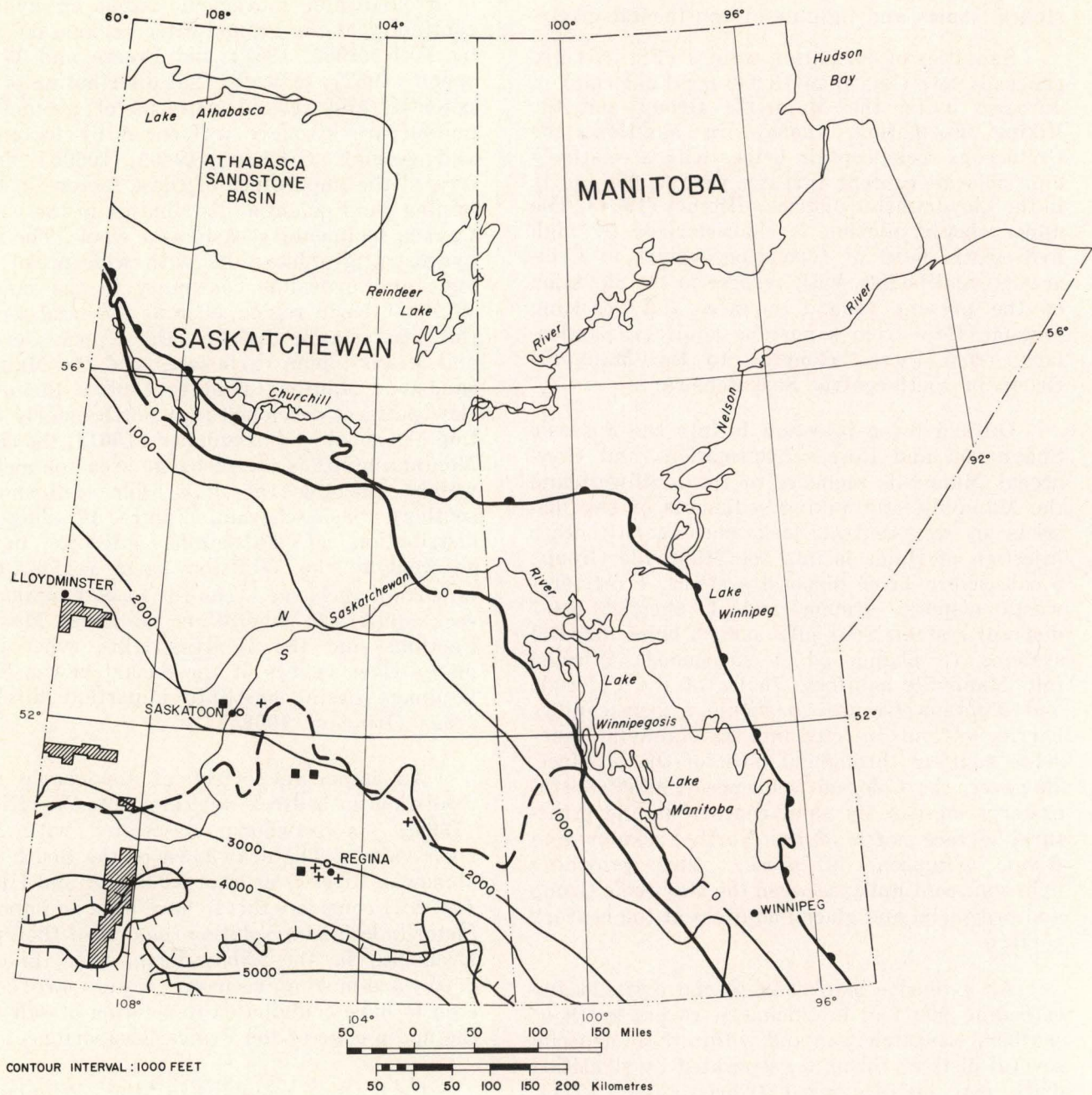


Fig. 15—The upper clastic division in Saskatchewan and Manitoba: Isopachs and distribution of subsurface waste-disposal systems.

- 1—southern perimeter of Precambrian Shield
- 2—limit of Cretaceous rocks
- 3—limit of Jurassic rocks
- 4—limit of Cenozoic rocks

- 5— potash brine injection
- 6— refinery and chemical-plant waste injection
- 7— salt-cavern brine

deposition are reflected in the sandstones, siltstones and shales of the upper part of the Montana Group, which are overlain unconformably by uppermost Cretaceous and Tertiary Sandstones, shales and lignites of continental origin.

Salinities of formation waters (Fig. 16) are generally low (less than 18,980 mg/l chloride) in Jurassic units, the Mannville Group and the Viking Formation, though in addition, the Cretaceous rocks contain brines with a relatively high chloride content (greater than 37,960 mg/l) in the Lloydminster district (Hitchon, 1964). The upper clastic division is characterized by high hydrostatic head of formation waters in Cretaceous sand bodies, with respect to the elevation of the present ground surface, and resulting artesian flow from sandstone aquifers, particularly from those belonging to the Mannville Group in south-central Saskatchewan.

Oilfield brine injection is into the Jurassic Shaunavon and Roseray Formations and Cretaceous Mannville sequence of the southwest and the Mannville and Viking sediments of two districts in west-central Saskatchewan. All other injection of fluids is into the Mannville Group: 5 salt-cavern brine disposal systems, 1 refinery-waste disposal system and 1 chemical-plant disposal system. Four pilot potash brine disposal systems (3 abandoned, 1 suspended) injected into Mannville aquifers. Shales of the Colorado and Montana Groups constitute a permeability barrier to fluids injected into the Mannville sandstone aquifers throughout most of the province. However, the Colorado sequence exhibits northeasterly increase in sand content on the structural terrace north of the North Saskatchewan River (Simpson, in press), thus providing hydraulic continuity between the Mannville Group and preglacial and glacial aquifers at the bedrock surface.

An extensive blanket of glacial drift, locally exceeding 900 feet in thickness, covers much of southern Saskatchewan and within these deposits several distinct till units, separated by stratified drift, may be recognized (Christiansen, 1971). Factors governing groundwater flow patterns in these sediments (Meneley, 1970) are horizontal permeability and lateral continuity of the stratified drift units (horizontal flow) and vertical permeability and thickness of the tills (rectilinear flow). Interbedded gravels, sands, silts and clays of dominantly fluvial origin also occur as pre- and early synglacial valley fill on the bedrock surface of southern Saskatchewan (Whitaker and Christiansen, 1972) and constitute important aquifers.

FLUID FLOW IN THE NORTHERN WILLISTON BASIN REGION

Consideration of the mathematical models of groundwater movement, based on hydraulic continuity of the groundwater regime, developed by Toth (1962, 1963) and Freeze and Witherspoon (1967), indicates that distribution of fluid potential and related patterns of groundwater motion are strongly influenced by topography and geology. Hitchon (1969a, 1969b) demonstrated the importance of these factors in determining fluid potential distribution in the western Canada sedimentary basin as a whole. The major hydrostratigraphic units with widespread lithologic and hydraulic continuity in the northern Williston basin region, such as the sandstones of the basal clastic division, the Upper Devonian and Mississippian carbonates and the Mannville sandstone aquifers, tend to control the overall flow pattern, developed in a northeasterly direction. As noted by Christopher (1961), the central Montana uplift is the recharge area for meteoric waters flushing the Palaeozoic sediments of southern Saskatchewan. Figure 17 shows the distribution of Palaeozoic outcrops in and adjacent to the Williston basin region. Other important recharge areas for Saskatchewan bedrock aquifers in general are the Rocky Mountain Foothills and the Cypress Hills, whereas all major river valleys of the Saskatchewan-Nelson Drainage basin constitute important discharge areas (Hitchon, 1969a).

An important effect of topography upon fluid flow in bedrock aquifers, noted by Hitchon (1969a), is drawdown, associated with major river valleys. The drawdown of the South Saskatchewan River is at least 5,000 feet and Hitchon (*op. cit.*) considers this to have been an important factor in localizing solution removal of the Prairie Evaporite in the Elbow-Venn area. Likewise, downward-moving recharge waters are considered to have contributed to solution of salt along the updip edge of the Prairie Evaporite.

Carbonate mounds in the Winnipegosis Formation along the western shore of Lake Winnipegosis (McCabe, 1967) are the sites of saline-spring discharge in southern Manitoba (Fig. 18) and probably also east-central Saskatchewan. van Everdingen (1971) considers that the brines of pre-Devonian Formations also contribute to this saline-spring discharge and that the springs, supplemented by diffuse seepage of brine, could effectively account for solution and removal of Devonian evaporites in Saskatchewan and Manitoba.

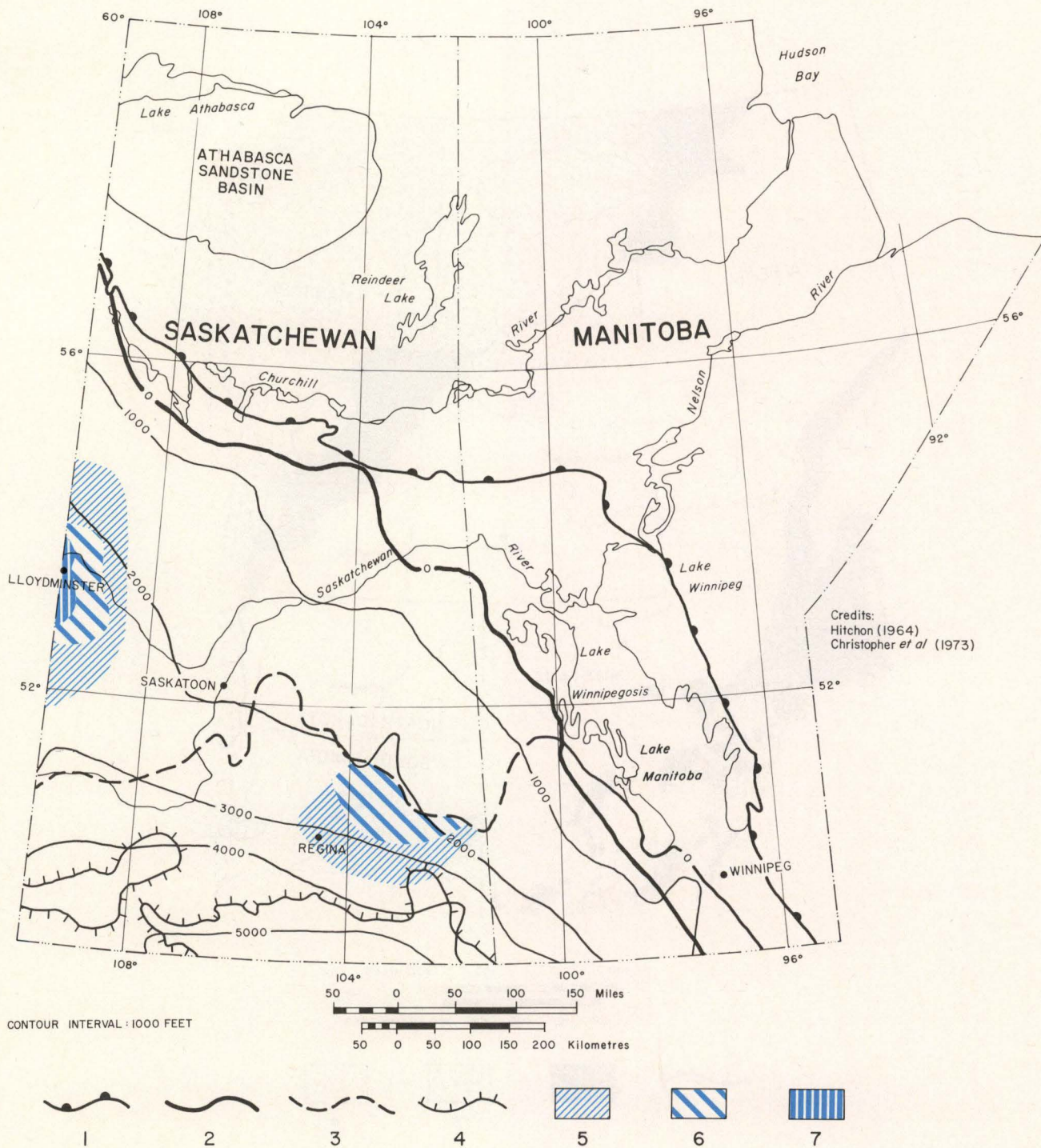


Fig. 16 — Chloride content of formation waters and isopachs of the upper elastic division in Saskatchewan and Manitoba.

- 1 — southern perimeter of Precambrian Shield
- 2 — limit of Cretaceous rocks
- 3 — limit of Jurassic rocks
- 4 — limit of Cenozoic rocks

- 5 — <18,980 mg/l
- 6 — 18,980-37,960 mg/l
- 7 — >37,960 mg/l

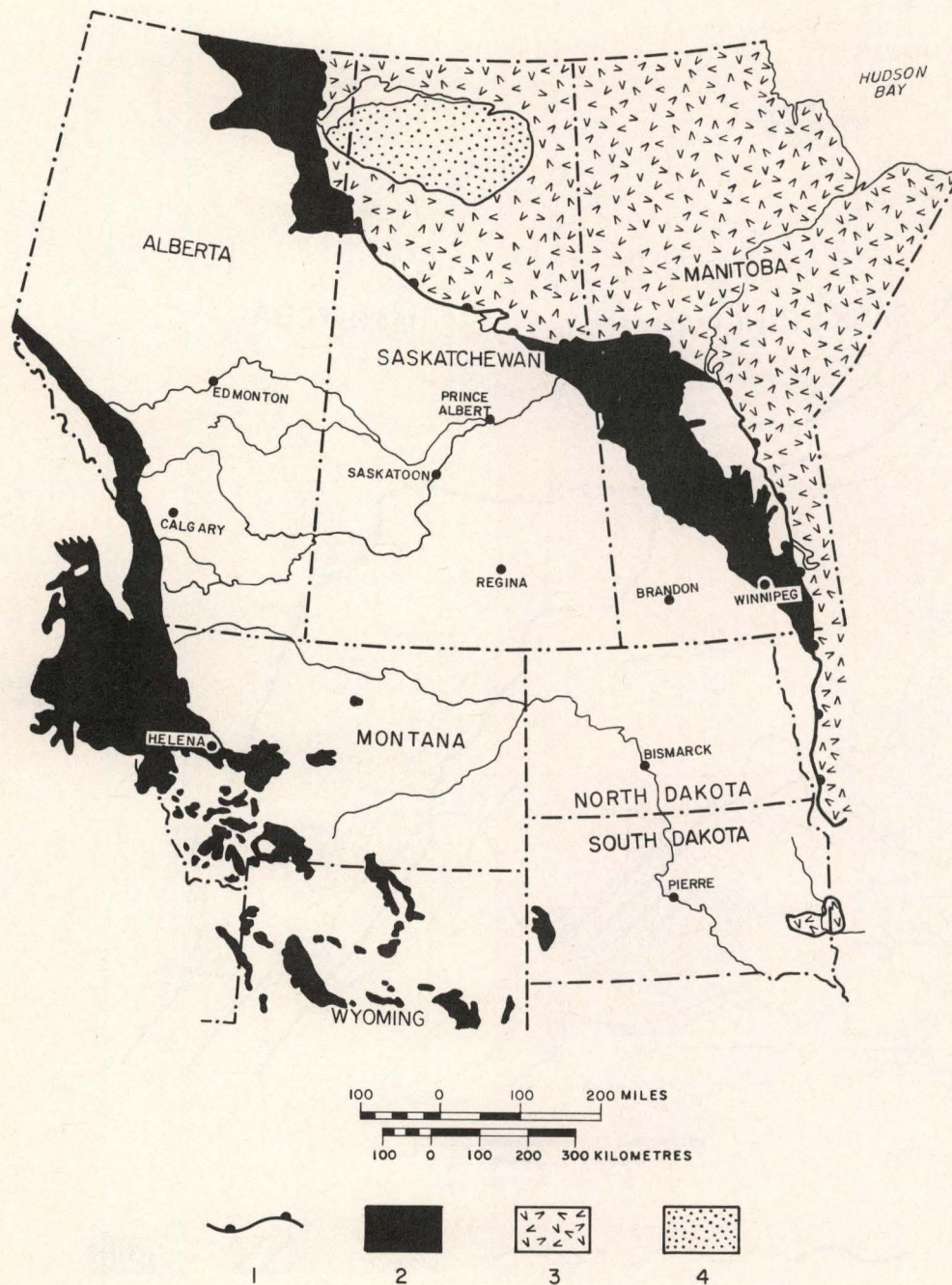


Fig. 17— Outcrop belts of Palaeozoic rocks in the Williston basin region and adjacent areas.

- 1— southern perimeter of Precambrian Shield 3— Precambrian rocks exposed
 2— Palaeozoic rocks exposed 4— Athabasca basin

The principal uses of formation waters in the northern Williston basin region are listed in Table 4. Additional possibilities of exploitation of formation waters in southern Alberta for calcium and magnesium are considered by Hitchon and Holter (1971) and may have application in Saskatchewan.

GROUNDWATER IN SHALLOW AQUIFERS

Groundwater use in southern Saskatchewan as estimated by Mollard (1965) amounted to 50 million gpd, such that 14 million gpd of this amount was derived through concentrated exploitation around major population centres, which occupy less than 3 per cent of the area under consideration. On the basis of these generalized estimates, he concluded that there would be 486 million gpd in addition available for use in the remaining 97,200 square miles of southern Saskatchewan considered. Groundwater of the Prairies has been shown to be a renewable resource by means of application of measurements of groundwater flow systems to solution of the hydrologic equation with respect to groundwater replenishment (Meyboom, 1967). Estimates of groundwater recharge expressed as a percentage of the total annual precipitation vary from less than 1 per cent to 7.5 per cent. A listing of projects utilizing groundwater and involving completion of wells in bedrock formations, kindly supplied by T. W. Rey and D. F. Bowhay of the Saskatchewan Department of the Environment is given in Appendix II.

The principal near-surface aquifer systems in Saskatchewan (Fig. 19; W. Meneley in Saskatchewan-Nelson Basin Board, 1972) are:

1. Valley aquifers, preglacial and glacial valley fill comprising laterally continuous sand and gravel deposits. Alluvial fine- to medium-grained sands predominate, ranging in thickness from 50 to 300 feet and with permeabilities of 2 to 4×10^{-2} cm/sec; incorporated coarse sands and gravels are typically less than 10 feet thick and discontinuous.

2. Blanket sand aquifers in the Empress aquifer system, consisting of fine- to medium-grained sands with permeabilities of 2 to

4×10^{-2} cm/sec, in extensive deposits underlain and overlain by till and bounded laterally by till or bedrock.

3. Inter-till aquifers, highly variable units of sand and gravel with permeabilities of 2 to 4×10^{-2} cm/sec, underlain and overlain by till and bonded laterally by till or bedrock.

4. Bedrock sandstone aquifers, which include sandstones of the Cretaceous Colorado and Mannville Groups and the Lower Palaeozoic Winnipeg and Deadwood Formations of central Saskatchewan, altogether comprising some 300 to 800 feet of fine- to medium-grained sandstones with permeabilities of 1 to 5×10^{-2} cm/sec. The Cretaceous sandstones are underlain by the carbonate aquifer and the Winnipeg-Deadwood succession. The southern boundary of the aquifer systems is a fresh-water/saline-water boundary, defined by the occurrence of water with more than 4,000 ppm total dissolved solids.

5. Carbonate aquifers are of greatest importance in east-central Saskatchewan, where Ordovician and Silurian limestones and dolomites occur below a variable drift cover. Farther west and northwest, Middle and Upper Devonian carbonates appear below the Cretaceous bedrock sandstone aquifers and may also occur at the bedrock surface.

Good hydraulic connections between ground- and surface-water systems are common and groundwater tables control the levels and chemistry of water in Saskatchewan lakes, notably in the Qu'Appelle and Souris River basins. The estimated net ground water yield of drift aquifers in southern Saskatchewan is 245,000 acre-feet per year, while that of the major bedrock aquifers in central Saskatchewan exceeds 2×10^6 acre-feet per year (*op. cit.*) Total dissolved solids in the groundwater of the major drift aquifers range from 1,000 to 4,000 ppm in concentration, most commonly falling in the range 1,000 to 2,500 ppm. On the basis of quality, this water is unsuitable for irrigation. Water in the bedrock aquifers of central Saskatchewan is of substantially better quality, but these aquifers are poorly known at the present time.

TABLE 4 - EXPLOITATION OF SALTS DISSOLVED IN SUBSURFACE
FORMATION BRINES OF THE NORTHERN WILLISTON BASIN REGION

WELL	DATE COMPLETED	TOTAL DEPTH (ft.)	DEPTH OF BRINE (ft.)	FORMATION	REMARKS
Neepawa No. 1 15-33-14-15W1	ca. 1913	1,798	1,185 1,460	Souris River Winnipegosis	brine evaporated at salt plant; well suspended
Neepawa No. 2 9-33-14-15W1	Feb. 1936	1,492	1,160 1,453	Souris River Winnipegosis	brine evaporated at salt plant; well abandoned
88 Dryden Chemicals Ltd. Brandon 16-10-10-18W1	Jul. 1967	3,447	3,267	Red River and Winnipeg	top of Winnipeg Fm. about 3,296 ft.; on stream Dec., 1967; brine electrolysed at caustic soda/chlorine plant; in operation
Dryden Chemicals Ltd. Brandon No. 2 WSW 16-10-10-18W1	Feb. 1969	2,290	2,190	Winnipegosis	brine electrolysed at caustic soda/chlorine plant; in operation
Simpson Oil Co. No. 1 2-9-29-25W2	Aug. 1931	3,448	3,438	Souris River	brine evaporated at salt plant 1932 to 1935; well abandoned, date unknown
Moose Jaw No. 1 6-33-16-26W2	Jan. 1932	3,419		Shaunavon	brine supplied to swimming pool

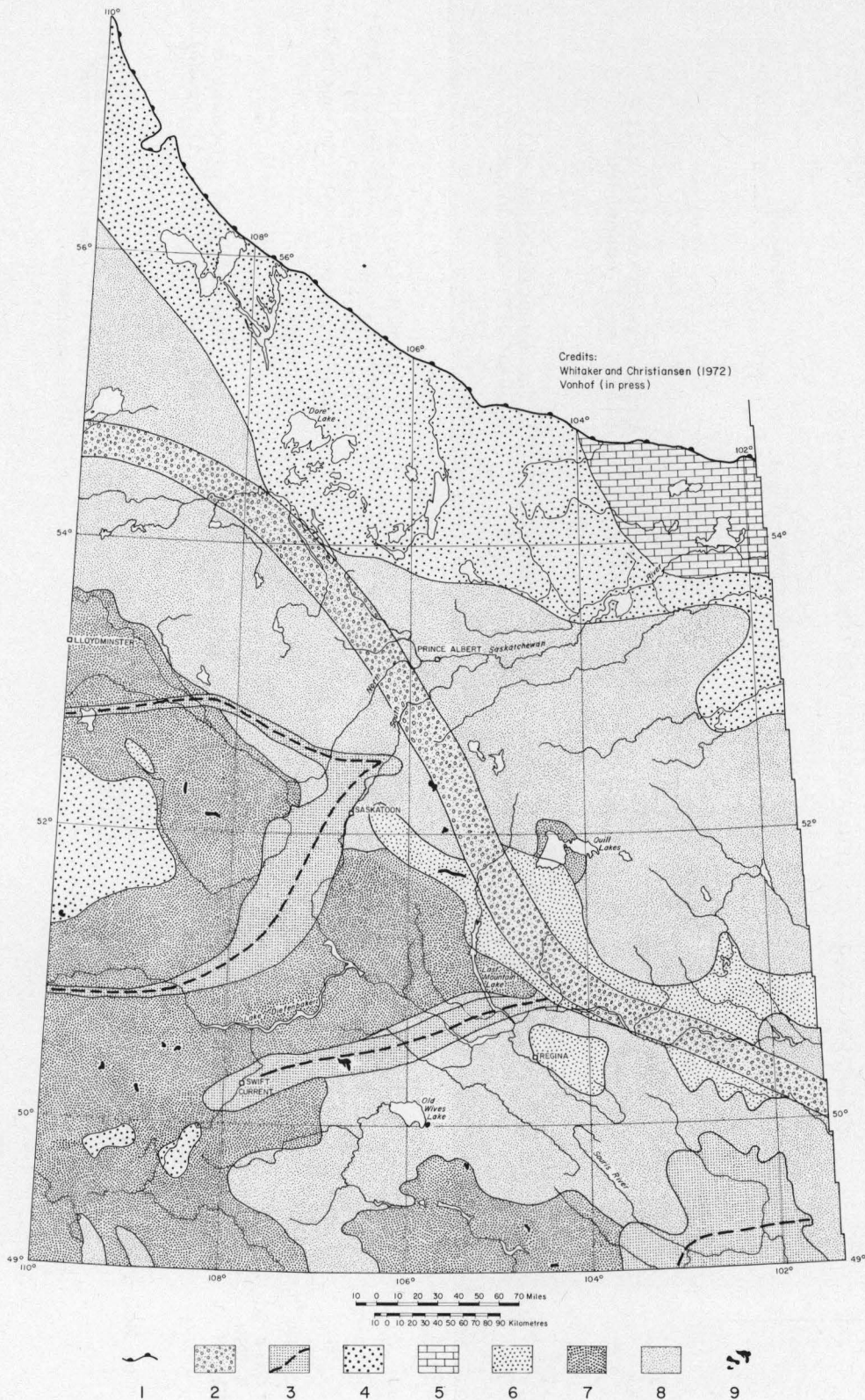


Fig. 19 — Principal aquifer systems of southern Saskatchewan.

- 1— southern perimeter of Precambrian Shield
- 2— Hatfield valley aquifer system (Empress Group)
- 3— other valley aquifers
- 4— bedrock sandstone aquifers
- 5— bedrock carbonate aquifers

- 6— blanket sand and intertill aquifers
- 7— predominantly bedrock sand aquifers
- 8— predominantly glacial sand aquifers
- 9— sodium sulphate deposits

SUBSURFACE WASTE-DISPOSAL SYSTEMS IN SASKATCHEWAN

GENERAL STATEMENT

Fluids injected into subsurface space in Saskatchewan (Table 1) include "natural" waste and non-waste and subordinate, "foreign" waste categories, in the terminology of van Everdingen and Freeze (1971). "Natural" fluids have constituents commonly found in the subsurface, though not necessarily in the disposal formation, and all others are termed "foreign". The "natural" wastes injected into deep aquifers in Saskatchewan are brines, produced during development of oilfields, extraction of potash from sylvite ore and solution enlargement of caverns in salt for underground gas storage. "Natural" non-waste fluids injected into subsurface space are oilfield brines, used for pressure maintenance in secondary recovery through water flooding, and the liquid petroleum gases (LPG) and natural gas, stored in salt caverns. The "foreign" wastes pumped into deep aquifers in Saskatchewan are those generated by two refineries at Regina and by a herbicide and chlor-alkali plant at Saskatoon.

OILFIELD BRINE INJECTION

Saskatchewan ranks second among Canadian provinces as a producer of crude oil and natural gas, contributing about 15 per cent of the nation's petroleum production. Crude oil and natural gas are produced from Ordovician to Cretaceous reservoir rocks, the distribution of which is shown in Figure 20. During 1972, 6,831 out of 8,133 wells capable of production yielded 86,623,826 bbls of crude oil, 86,402,886 Mscf of natural gas and 1,478,576 bbls of liquefied petroleum gases, altogether valued at \$223,813,604. Total cumulative production of crude oil to December 31, 1971, was 1.218 billion barrels and the gross value of sales reached a total of \$2,720,141,300. Total cumulative production of natural gas to December 31, 1972, was 610.972 billion cu. feet. The total cumulative net cash expenditures of the petroleum industry in Saskatchewan amounted to 2.055 billion dollars for the period 1947 to 1971.

Total original recoverable reserves of crude oil in Saskatchewan to Dec. 31, 1972, were estimated to be 2.042 billion barrels and therefore remaining recoverable reserves amounted to about 823.728 million barrels. Medium- and high-gravity crude oils in the Mississippian reservoirs

of southeastern Saskatchewan accounted for 61.02 per cent of original recoverable reserves, while Palaeozoic reservoirs as a whole contained 63.08 per cent of the total reserves. Medium-gravity crude oil made up 54.9 per cent of original reserves, high-gravity crude oil 36.21 per cent and low-gravity crude oil 8.89 per cent. Remaining recoverable reserves of natural gas are estimated to be 992.980 billion cu. feet.

The distribution of oil and gas production in the study area and Saskatchewan Government-designated disposition areas I through IV are presented in Figure 20. Table 5 shows total cumulative volumes of brines, injected into the upper clastic and carbonate-evaporite divisions respectively, and ranges in both injection rate and injection pressure for each of the disposition areas. Only 51 wells are classified as brine disposal wells, while 1,610 more are pressure maintenance wells, in which brine produced with the oil is used to displace crude oil and thus increase recovery. Depths of injection formations range from 1,750 feet in area I to 6,500 feet in area IV. Injection rates are low to moderate (1 to 200 US g/m), but injection pressures range from zero to as much as 3,000 psig in the carbonate-evaporite division of area IV, which receives 53.9 per cent of all oilfield brines injected into deep aquifers in Saskatchewan.

POTASH BRINE DISPOSAL

In Canada, extensive subsurface occurrences of potash deposits are largely restricted to the Devonian System of the Prairie provinces and the Mississippian System of the Atlantic provinces. However, only in Saskatchewan is there commercial production of potash from the Middle Devonian Prairie Evaporite, which in 1972 maintained the nation's status of leading exporter and second most important producer of this mineral commodity. The stratigraphy of the Prairie Evaporite was recently elaborated by Holter (1969) and problems in exploration for economic potash deposits of this succession are considered by Holter (1971) and Ann Fuzesy (Saskatchewan Department of Mineral Resources, 1973).

The Prairie Evaporite is encountered at depths of 1,300 to 9,000 feet in the Saskatchewan subsurface and attains a maximum thickness of more than 700 feet in the Saskatoon district. The potash deposits are the Esterhazy, Belle Plaine

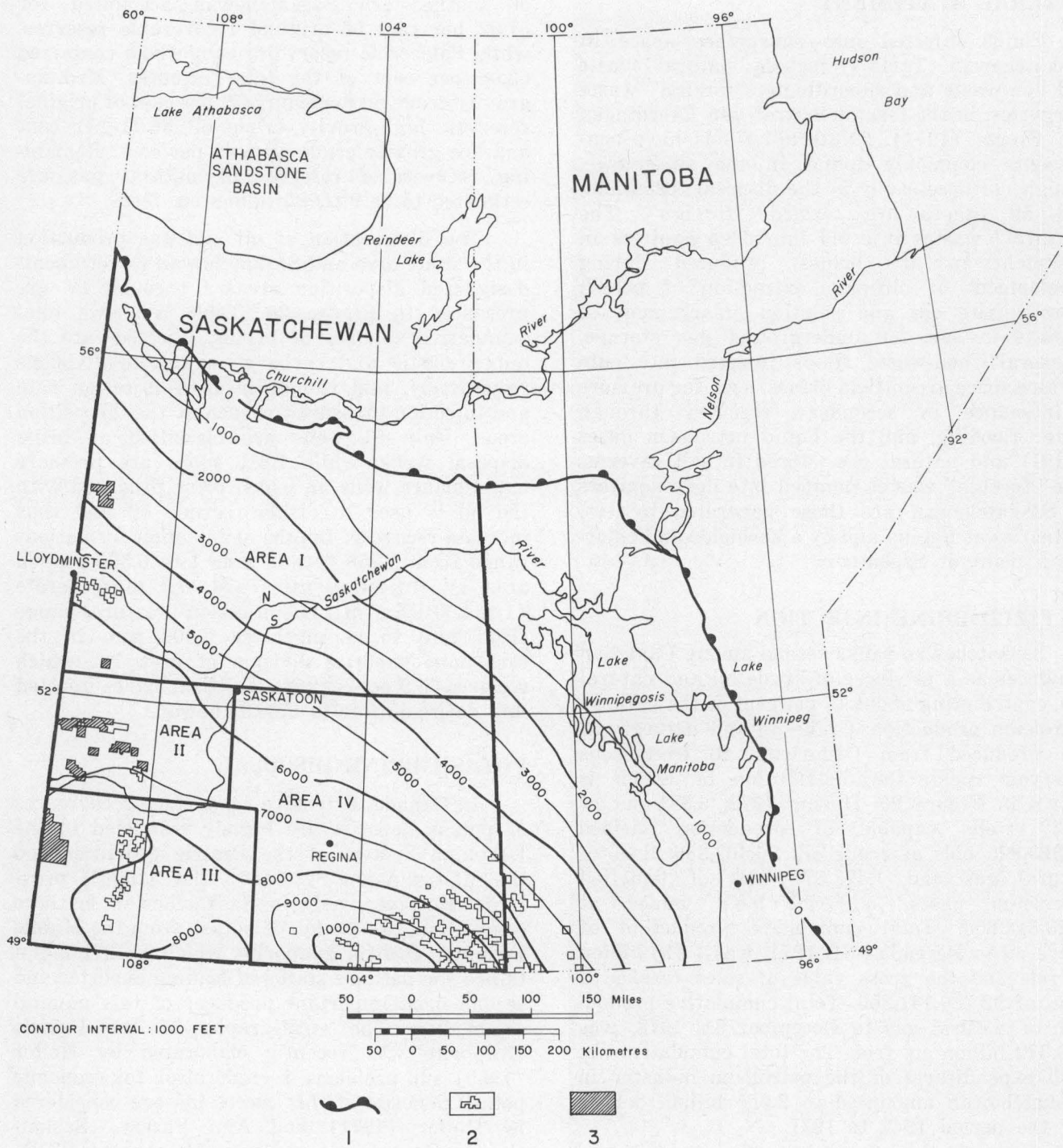


Fig. 20 — Distribution of crude oil and natural gas production on isopach map of Phanerozoic sequence, Saskatchewan and Manitoba.

1— southern perimeter of Precambrian Shield

2— oil production

3— natural gas production

TABLE 5 - SUBSURFACE FLUID-INJECTION SYSTEMS IN SASKATCHEWAN: OIL FIELD BRINE INJECTION

DISPOSITION AREA	DISPOSAL DEPTH (ft)	YEAR FIRST INJECTION	INJECTION RATE (US g/m)	INJECTION PRESSURE (psig)	TOT. CUM. VOL. INJECTED TO END 1972 ¹ (bbls)
I	1,750	1953	1-40	0-600	(1) 82,970,000
	2,280	1952	—	—	(2) 160,000
					(3) 83,130,000
II	2,300	1956	1-20	0-2,000	(1) 85,010,000
	2,750	1956	1-20	0-900	(2) 69,210,000
					(3) 154,220,000
III	3,200-4,400	1956	1-200	0-1,600	(1) 848,280,000
	4,700	1969	180	2,100-2,400	(2) 8,370,000
					(3) 856,650,000
IV	2,900	1956	1-40	0-2,200	(1) 42,580,000
	3,800-6,500	1957	1-50	0-3,000	(2) 1,335,750,000
					(3) 1,378,330,000

37

¹ Subtotals (1) and (2) for upper clastic and carbonate-evaporite divisions respectively; (3) is total for each disposition area.

and Patience Lake Members (Fig. 21), listed in order of decreasing age, which occur in the uppermost 200 feet of the Prairie Evaporite. Each member consists of layers of sylvinite, a mixture of sylvite and halite, bounded laterally by carnallitic sylvite or carnallitic halite, so that carnallite is relatively abundant in the north and sylvite (up to about 30 per cent) and insoluble material appear in increasing proportions farther south. Maximum thicknesses of the Esterhazy, Belle Plaine and Patience Lake Members are 103 feet, 151 feet and 88 feet respectively.

Potash was first produced successfully in Saskatchewan in 1958 by Potash Company of America on completion of a shaft started in 1956, although production was suspended from late 1959 to 1965 as a result of seepage of water into the shaft. Subsequent exploration for potash in

Saskatchewan has been largely concentrated in a belt 120 miles wide, extending southeastward from Biggar in central Saskatchewan to the Manitoba border and covering about 21,000 square miles, as well as in an area of 936 square miles in the Unity district. Currently potash is produced at nine mines, in which conventional underground methods are employed, and at one plant, where mining is by controlled solution removal of potash minerals at depth. Conventional room-and-pillar mining is applied, where potash ore occurs at depths of up to 3,500 feet. Below this depth, mine-face stability cannot be ensured in Saskatchewan and solution mining is favoured. Potash deposits at a depth of nearly 5,000 feet are mined at the solution-mining operation of Kalium Chemicals Limited at Belle Plaine, west of Regina. The distribution of current potash production is shown in Fig. 22.

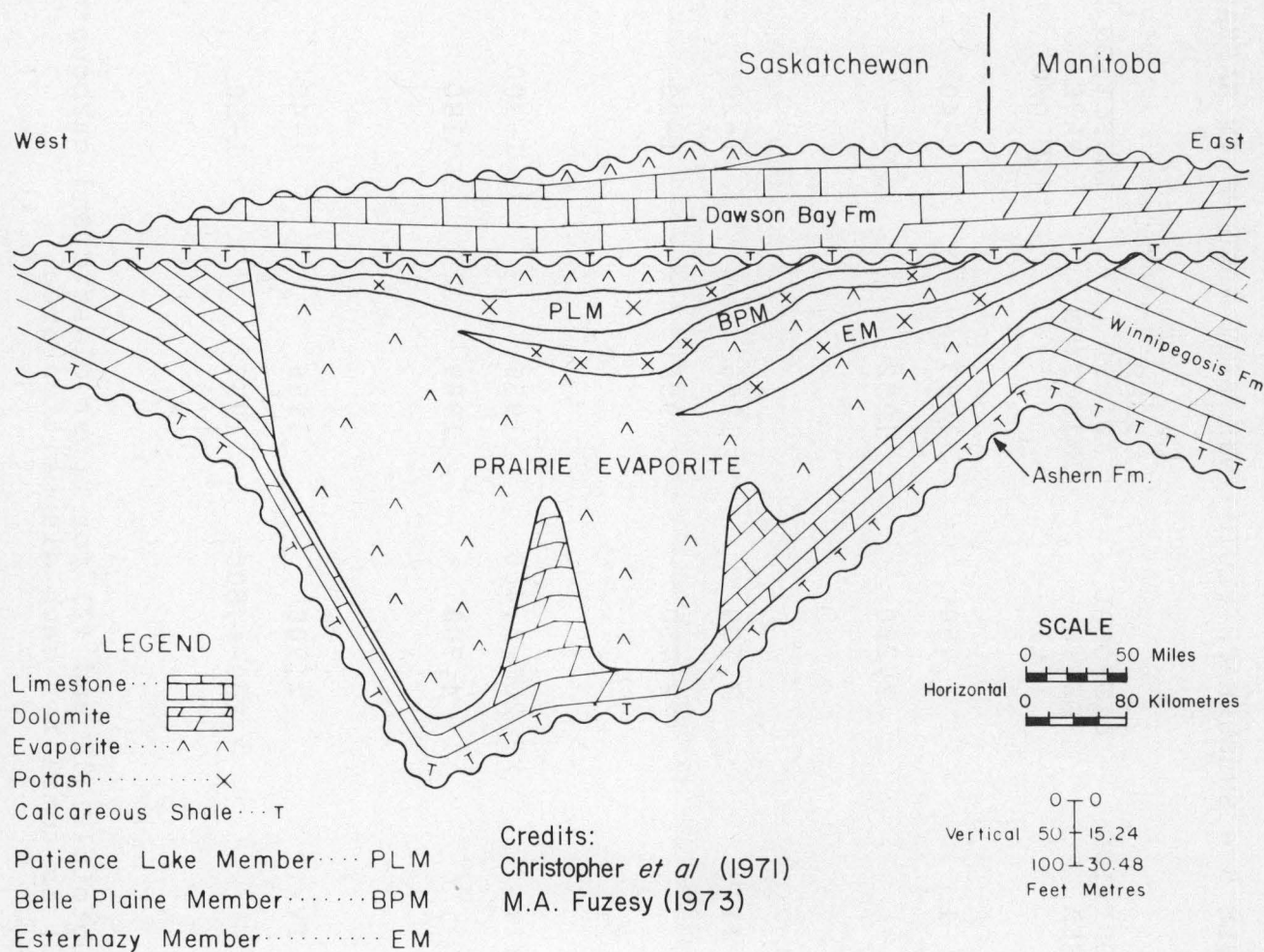


Fig. 21 — East-west diagrammatic cross-section of Middle Devonian rocks in Saskatchewan and Manitoba

TABLE 6 - POTASH MINING OPERATIONS AND BRINE DISPOSAL SYSTEMS IN SASKATCHEWAN

MINE	LOCATION	OPERATIONS COMMENCED	ON STREAM	CAPACITY (MM tons/year)		PRODUCTION TO END 1972	WASTE-DISPOSAL SYSTEM
				KCl	K ₂ O		
Sylvite of Canada Limited	Rocanville	Jan., 1968	Sep., 1970	1.2	0.73	— ²	deep-well injection; surface lagoons
International Minerals and Chemical Corp. (Canada) Limited	Esterhazy	May, 1963	Apr., 1967	1.7	1.05	— ²	deep-well injection; surface lagoons
International Minerals and Chemical Corp. (Canada) Limited	Esterhazy	Jun., 1957	Jun., 1962	2.1	1.28	— ²	deep-well injection; surface lagoons
Alwinal Potash of Canada Limited	Lanigan	Oct., 1964	Oct., 1968	1.0	0.6	— ²	surface lagoons
Kalium Chemicals Limited	Belle Plaine	May, 1963	Oct., 1964	1.5	0.94	— ²	deep-well injection; surface lagoons
Central Canada Potash Co. Limited	Colonsay	Jan., 1966	Sep., 1969	1.5	0.9	— ²	deep-well injection; surface lagoons
Allan Potash Mines Limited	Allan	Aug., 1964	May, 1968	1.5	0.9	— ²	deep-well injection; surface lagoons
Potash Company of America	Patience Lake	Apr., 1954	Dec., 1958	0.76	0.46	— ²	surface lagoons
Duval Corporation of Canada	Saskatoon	Dec., 1965	May, 1968	1.2	0.73	— ²	deep-well injection; surface lagoons
Cominco Limited	Vanscoy	Sep., 1965	Mar., 1969	1.2	0.72	— ²	surface lagoons
Western Potash Corporation Ltd. ¹	Unity	1951	—	—	—	—	—

¹ Became Continental Potash Corporation Limited in 1955. Shaft abandoned 1960.

² Production by company is confidential, however total production to end of 1972 was 26 million tons of K₂O or approximately 100 million tons of ore.

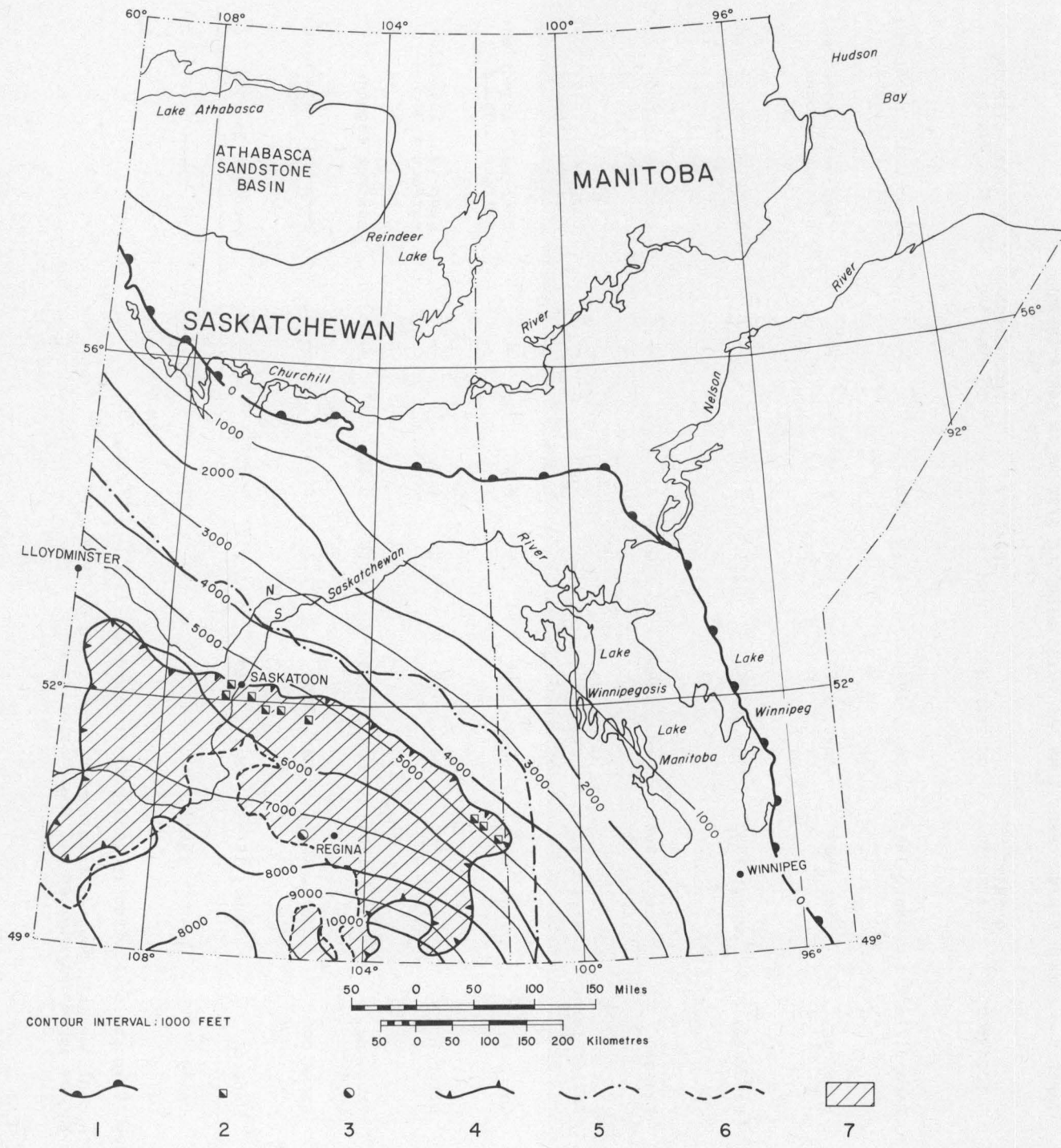


Fig. 22 — Distribution of potash production from the Prairie Evaporite (Middle Devonian) on isopach map of Phanerozoic sequence, Saskatchewan and Manitoba.

- | | |
|---|--|
| 1— southern perimeter of Precambrian Shield | 5— limit of salt |
| 2— shaft mining | 6— area where Prairie Evaporite absent |
| 3— solution mining | 7— area of potash production potential |
| 4— limit of soluble potassium minerals | |

Costs of Saskatchewan potash plants have been in the range of \$60 million to \$81 million, and a total capital investment of the order of \$693.5 million is represented by the plants presently in operation. Production of potash for the year 1972 was 4,329,457 short tons of K_2O at a value of \$146,013,985. The total cumulative production of potash to the end of 1972 amounted to 26,235,344 tons of K_2O , valued at \$810,155,877. Total recoverable reserves of commercial potassium minerals are estimated at 74 billion short tons of K_2O (118 billion short tons of KCl), 65 billion of which (110 billion short tons of KCl) may be recovered by solution mining. Fig. 23 shows the surface plant of the Central Canada Potash Co., Limited, at Colonsay, which is the latest potash-mining operation to initiate a deep-well disposal system for waste brines.

Potash brine disposal systems of Saskatchewan are listed in Table 7. Eight of these systems are currently in operation. Fig. 24 shows the areas in which shaft and solution mining of potash may be developed in the future and thus gives an indication of further areas, which will be considered for deep-well disposal of waste brines. Five of the systems listed are pilot disposal projects now suspended or abandoned and were used in connection with experiments on controlled solution of the Prairie Evaporite. Table 8 lists these latter solution systems as well as other brining well systems, exclusive of caverns in halite for gas storage. Current systems are characterized by high injection rates (175 to 1,100 U.S. g/m) and moderate to high injection pressures (130 to 910 psig), as demonstrated in Fig. 25. Such systems involve injection of large volumes of brine (Table 9) for the duration of the life of a mine (1 to 2 decades), with disposal discontinued for short periods of maintenance only during that time. In the vicinity of shaft mines, disposal is into aquifers of the basal clastic division and that part of the carbonate-evaporite division below the Prairie Evaporite, to minimize the danger of flooding within the mine workings. Multizone injection, with disposal intervals in both of these divisions, is employed in two wells operated by the International Minerals & Chemical Corporation (Canada) Limited and in two wells belonging to Sylvite of Canada Ltd. It is of interest to note that potash shaft mines themselves represent some two billion cubic feet of potential subsurface storage space.

SALT-CAVERN BRINE DISPOSAL

Caverns in halite of the Prairie Evaporite are used by the Saskatchewan Power Corporation for dry storage of natural gas and by Dome Petroleum Limited and Procor Limited respectively for storage of liquified petroleum gases. There are seven salt-cavern storage facilities in Saskatchewan with a total of eighteen caverns (Fig. 26, Table 10) giving an aggregate cavern storage capacity of 8,250,000 bbls. The subsurface waste-disposal systems associated with these cavern-storage facilities are listed in Table 11. Of the ten wells listed, only five are presently in operation, with moderate injection rates (150 to 300 U.S. g/m) and frequently high injection pressures of up to 1,750 psig, as shown in Fig. 27. The life of a salt-cavern brine-disposal well is determined by the rate of growth of the cavern or caverns, with which it is associated, that is, injection may continue for a period of a year or more. Disposal has been into formations at moderate depths (1,712 to 3,571 feet), referable to the carbonate-evaporite division and lowermost part of the upper clastic division. Even natural waste brines may require filtering for removal of clay prior to deep-well disposal and Fig. 28, courtesy of Domtar Chemicals, Ltd., shows surface equipment for pre-injection treatment of waste.

REFINERY AND CHEMICAL-PLANT WASTE DISPOSAL

Disposal of refinery wastes into the subsurface is effected by two operators in the Regina district (Table 13). Consumers' Co-operative Refineries Limited inject spent caustic containing phenols and sulphides into the lower part of the upper clastic group at low injection rates (3 U.S. g/m) and low pressure (gravity). Up to September, 1972, the waste contained about 70 per cent receiver water, with spent caustic making up the remainder. Imperial Oil Enterprises, Ltd., disposes of sour water (680 to 740 bbls per day) and spent caustic (15 to 30 bbls per day) into limestones near the top of the carbonate-evaporite group (Table 14), the volumes depending on the crude rate. Injection rates are low (22 U.S. g/m) and pressure moderate (350 psig). Table 13 includes data on disposal of refinery wastes by Imperial Oil Enterprises, Ltd., at Viriden, Manitoba, and by Husky Oil Operations Ltd., at Lloydminster. Fig. 29 shows monthly average injection rates and pressures of the two refinery subsurface disposal systems in Saskatchewan.

TABLE 7 - SUBSURFACE FLUID INJECTION SYSTEMS IN SASKATCHEWAN: POTASH BRINE DISPOSAL

REF NO.	DISPOSAL WELL	TOP OF DISPOSAL INTERVAL (ft)	DISPOSAL FORMATION	DATE FIRST INJECTION	INJECTION RATE (US g/m)	INJECTION PRESSURE (psig)	TOT.CUM.VOL. INJECTED TO END 1972 (bbls)
1	Sylvite St Marthe 1-14-17-30W1	3,670 4,413	Interlake & Winnipeg	Dec. 30, 1971	175	190	1,480,000
2	Sylvite St Marthe 3-20-17-30W1	3,710 4,448	Interlake & Winnipeg	Jan. 21, 1972	245	270	2,180,000
3	IMC Gerald SWD 14-27-19-32W1	3,690 4,578	Interlake & Winnipeg	Aug. 8, 1972	590	130	1,170,000
4	IMC Yarbo SWD 10-14-20-33W1	3,850 4,593	Interlake & Winnipeg	Jul. 16, 1968	1,100	910	30,640,000
5	General Petroleums ¹ Kutawagon 6-29-30-21W2	1,773	Mannville	Jan. 9, 1961	— ²	—	270,000
6	SWP 2 Boulder Lake ¹ 16-18-30-23W2	1,448	Mannville	1963	— ³	—	—
7	Stan Chem Stony Beach ¹ 4-11-17-24W2	2,488	Mannville	1961	— ²	—	2,600,000
8	Kalium Belle Plaine 9-23-17-24W2	3,745	Souris Valley	Nov. 2, 1971	320	80	3,070,000
9	Imp Findlater ¹ 16-10-21-25W2	3,275	Birdbear	1962	— ²	—	—
10	C.C.P. Viscount Disposal 2-21-34-27W2	4,631	Deadwood	Mar. 15, 1973	610	500	760,000 ⁴
11	APM Allan Disposal 13-22-34-1W3	4,692	Deadwood	Jul. 23, 1971	500	500	13,940,000
12	DSP 4-2B-37-6W3 ¹	1,535	Mannville	1962	2	—	—
13	Duval Saskatoon SWD 8-13-36-7W3	4,645	Deadwood	Mar. 12, 1971	805	740	7,330,000
	¹ Pilot disposal system	² Abandoned well	³ Suspended well	⁴ Injection to April 30, 1973			



Fig. 23 — Surface facilities of the Central Canada Potash Co., Limited, potash-mining operation at Colonsay, Saskatchewan (photograph courtesy of Central Canada Potash Co., Limited)

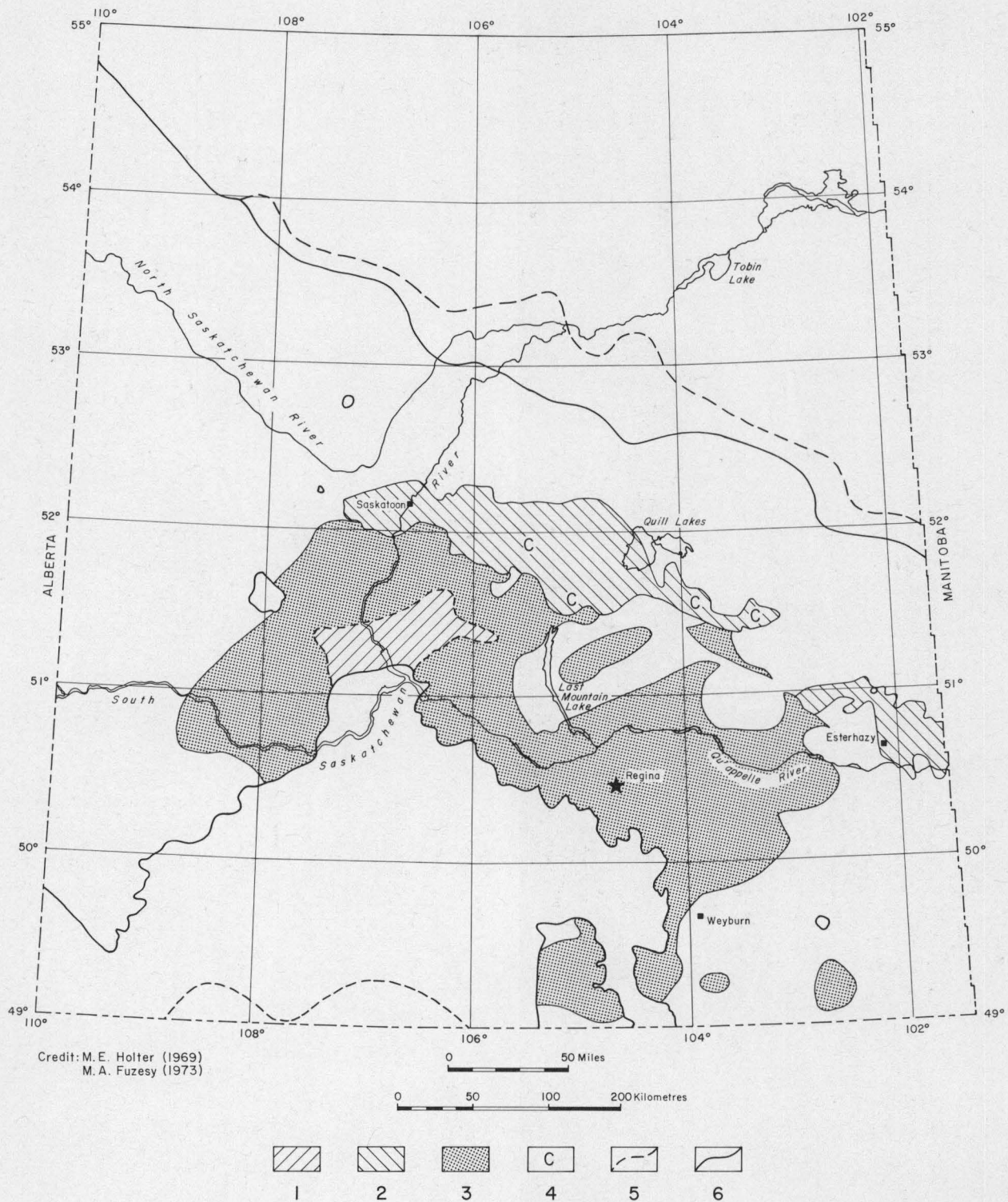


Fig. 24 — Commercial potash-mining potential of southern Saskatchewan.

- 1— salt partly removed
- 2— favourable for shaft mining
- 3— favourable for solution mining

- 4— problems with carnallite possible
- 5— edge of anhydrite
- 6— edge of salt

TABLE 8 - CONTROLLED SOLUTION REMOVAL OF PRAIRIE EVAPORITE, EXCLUSIVE OF STORAGE CAVERN DEVELOPMENT IN SASKATCHEWAN

SOLUTION WELL(S)	COMPLETION DATE/ON STREAM	SOLUTION INTERVAL (ft.)	CURRENT STATUS	FRESH-WATER SOURCE	BRINE-DISPOSAL FORMATION	REMARKS
1. General Petroleum Kutawagon 6-29-30-21 W2	Jan. 1958	3,432-3,490	abandoned	surface	Mannville	solution-mining test well
2. Lumsden Potash No. 1 ¹ Bethune 2-17-20-23 W2	Dec. 1966	4,900	suspended	Mannville	surface	solution-mining test well
3. Lumsden Potash No. 3 Bethune 2-17-20-23 W2	Apr. 1967	—	suspended	Mannville	surface	solution-mining test well
4. Lumsden Potash No. 4 Bethune 2-17-20-23 W2	Aug. 1967	4,900	suspended	Mannville	surface	solution-mining test well
5. Lynbar Duval 4-22-25-23 W2	Jan. 1967	4,100	suspended	surface	surface	solution-process experimental well
6. SWP Boulder Lake 16-18-30-23 W2	Jul. 1963	3,500	suspended	surface	Mannville	experimental potash-brine test well
7. SWP 3 Boulder Lake 16-18-30-23 W2	Aug. 1963	3,500	suspended	surface	Mannville	experimental potash-brine test well
8. Stan Chem Stony Beach No. 2 12-11-17-24 W2	Apr. 1961	5,600	abandoned	Mannville	Mannville	solution-mining test well
9. Stan Chem Stony Beach No. 4 12-11-17-24 W2	May 1961	5,600	abandoned	Mannville	Mannville	potash solution-mining test well
10. Kalium Chemicals Limited (secs. 24, 25 & 26 -17-24 W2)	Oct. 1964	—	operating	surface	Souris Valley	the only commercial potash solution-mine operation in the world
11. Imperial Findlater Potash 16-10-21-25 W2	Apr. 1962	5,000	abandoned	Mannville	Birdbear	potash pilot well
12. Imperial Findlater Potash 16A-10-21-25 W2	Sep. 1962	5,000	abandoned	Mannville	Birdbear	potash pilot well
13. Northern Rochdale 3-26-37-5 W3	1967	3,361-3,590	operating	surface	Mannville	brining well
14. Northern Rochdale 4-26-37-5 W3	Jul. 1962	3,410-3,566	operating	surface	Mannville	brining well
15. Northern Rochdale 5-26-37-5 W3	1967	3,362-3,570	operating	surface	Mannville	brining well
16. DSP 4-2-37-6 W3	May 1962	3,200	abandoned	surface	Mannville	potash solution-mine test well
17. DSP 4-2A-37-6 W3	Jun. 1962	3,200	abandoned	surface	Mannville	potash solution-mine test well
18. Prairie Salt Co. No. 3 14-4-40-22 W3	1967 ?	3,600	operating	surface	Duperow ¹	brining well
19. Prairie Salt Co. No. 4 14-4-40-22 W3	1969	3,600	operating	surface	Duperow ¹	brining well
20. Prairie Salt Co. No. 1 15-4-40-22 W3	Feb. 1947	3,600	suspended	surface	surface	brining well
21. Prairie Salt Co. No. 2 15-4-40-22 W3	Jun. 1947	3,600	plugged back to SWD	surface	surface	brining well
22. Verbata No. 2 7-24-41-24 W3	—	—	abandoned	Belly River	surface	poor core recovery due to solution in unsaturated drilling fluid

Note: Solution interval, unless a sonar survey was available, is the approximate landed casing depth.

¹ Prior to 1973 disposal was to a surface lagoon and lake

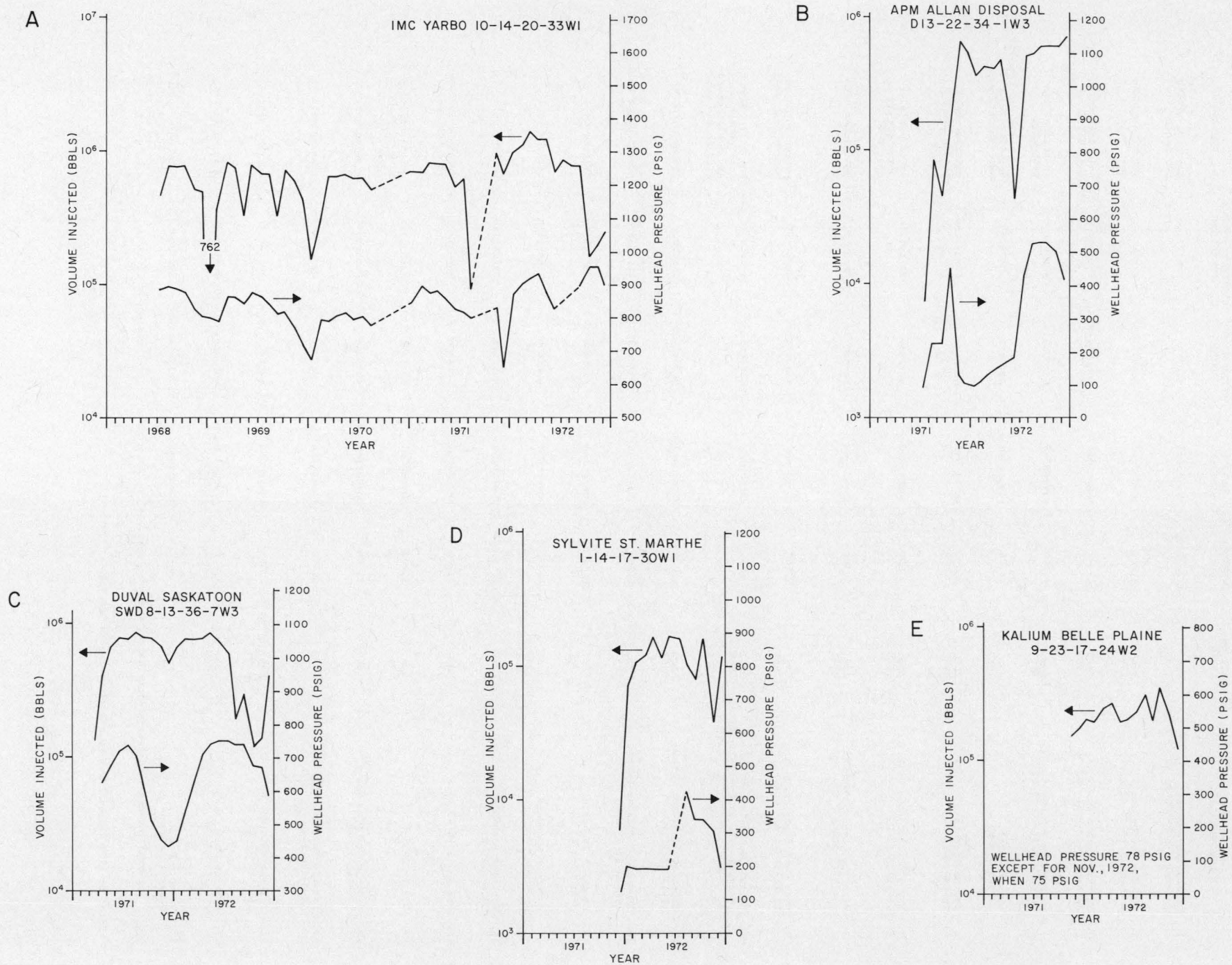


Fig. 25 — Operation histories of potash-mine subsurface-disposal systems in Saskatchewan as time series of monthly average injection rates and pressures.

TABLE 9 - COMPOSITION OF POTASH-MINE WASTE BRINES INJECTED INTO THE
CCP VISCOUNT DISPOSAL 2-21-34-27 W2 WELL

INORGANIC CONSTITUENTS	CONCENTRATION (PPM)
sodium	93,600
potassium	41,200
calcium	1,746
magnesium	1,107
chloride	184,100
sulphate	1,648
bicarbonate	128

PHYSICAL PROPERTIES

specific gravity	1.2
pH	7.4
injection temperature (°F)	0-80
suspended solids (ppm)	35

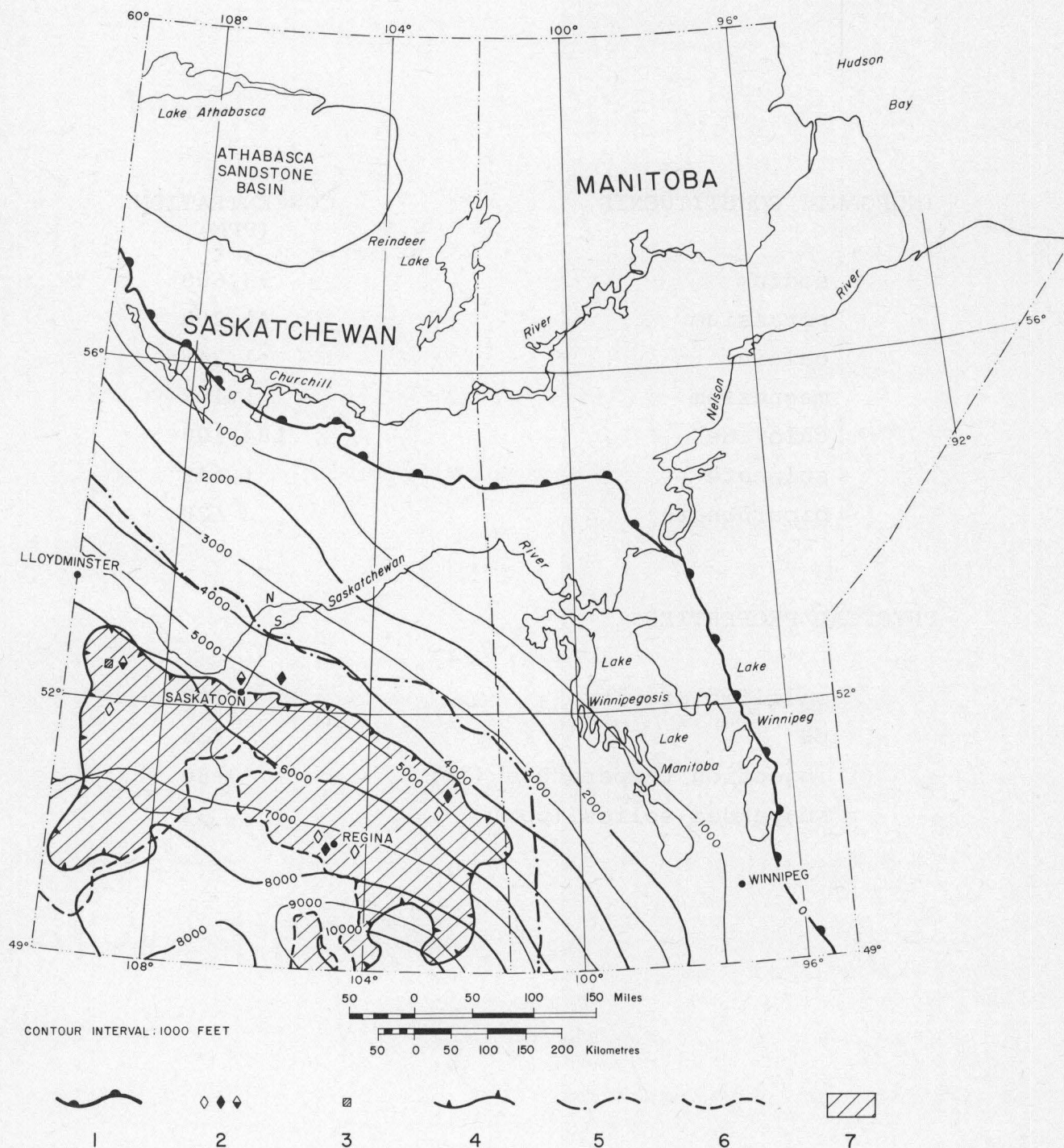


Fig. 26 — Distribution of caverns in halite of the Prairie Evaporite (Middle Devonian) on isopach map of Phanerozoic sequence, Saskatchewan and Manitoba.

- | | |
|---|--|
| 1— southern perimeter of Precambrian Shield | 4— limit of soluble potassium minerals |
| 2— LPG storage cavern, natural gas storage cavern and chemical-plant facility | 5— limit of salt |
| 3— aquifer natural gas storage | 6— area where Prairie Evaporite absent |
| | 7— area of potash production potential |

TABLE 10 - SALT-CAVERN STORAGE FACILITIES IN SASKATCHEWAN

REF. NO.	SALT-CAVERN STORAGE FACILITY	PRODUCT STORED	NUMBER OF CAVERNS	YEAR FIRST STORAGE	AVERAGE CAVERN DEPTH (ft)	TOT. STORAGE CAPACITY TO END 1972 (bbls)
1	Dome Melville (sec. 29-22-6W2)	LPG	5	1962	3,470	3,000,000
2	SPC Brewer (sec. 15-23-6W2)	natural gas	1	1963	3,370	290,000
3	Pacific Edenwold (sec. 22-16-18W2)	LPG	2	1966	5,060	800,000
4	SPC Regina (sec. 27-16-20W2)	natural gas	2	1964	5,350	870,000
5	Procor Regina (sec. 29-17-20W2)	LPG	4	1972	5,180	900,000
6	SPC Prud'homme (sec. 12-38-28W2)	natural gas	2	1965	3,120	990,000
7	Dome Kerrobert (sec. 34-33-22W3)	LPG	2	1971	4,360	400,000

TABLE 11 - SUBSURFACE FLUID INJECTION SYSTEMS IN SASKATCHEWAN: SALT-CAVERN BRINE DISPOSAL

REF. NO.	DISPOSAL WELL	TOP OF DISPOSAL INTERVAL (ft)	DISPOSAL FORMATION	DATE FIRST INJECTION	INJECTION RATE (US g/m)	INJECTION PRESSURE (psig)	TOT. CUM. VOL. INJECTED TO END 1972 (bbls)
1	Dome Melville 1 SWD 6-29-22-6W2	1,750	Souris Valley	Sep. 16, 1958	— 1	—	7,740,000
2	Dome Melville 2 SWD 6-29-22-6W2	1,740	Souris Valley	Apr. 9, 1967	240	gravity	8,450,000
3	Dome Melville 3 SWD 3-29-22-6W2	1,794	Souris Valley	Jun. 1, 1969	250	gravity	4,100,000
4	SPC Brewer 5-15-23-6W2	1,600	Mannville	1963	— 2	—	2,320,000 ³
5	Pacific SWD 1 Edenwold 1-22-16-18W2	2,253	Mannville	May 16, 1963	— 2	1,000	7,000,000
6	SPC Regina 10-27-16-20W2	2,530	Mannville	Nov. 28, 1963	— 2	1,200	6,960,000 ³
7	Procor Regina No. 1 SWD A7-29-17-20W2	2,510	Mannville	May 12, 1972	200	950	1,390,000
8	Procor Regina No. 2 SWD B7-29-17-20W2	3,571	Souris Valley	Jul. 28, 1972	300	510	1,250,000
9	SPC Prud'homme 11-12-38-28W2	1,712	Mannville	Feb. 10, 1965	— 2	1,100	7,920,000 ³
10	Dome Kerrobert 1 SWD 6-34-33-22W3	3,260	Duperow	Apr. 1, 1971	350	1,750	3,800,000

¹ Abandoned well

² Suspended well

³ Volumes are estimates only

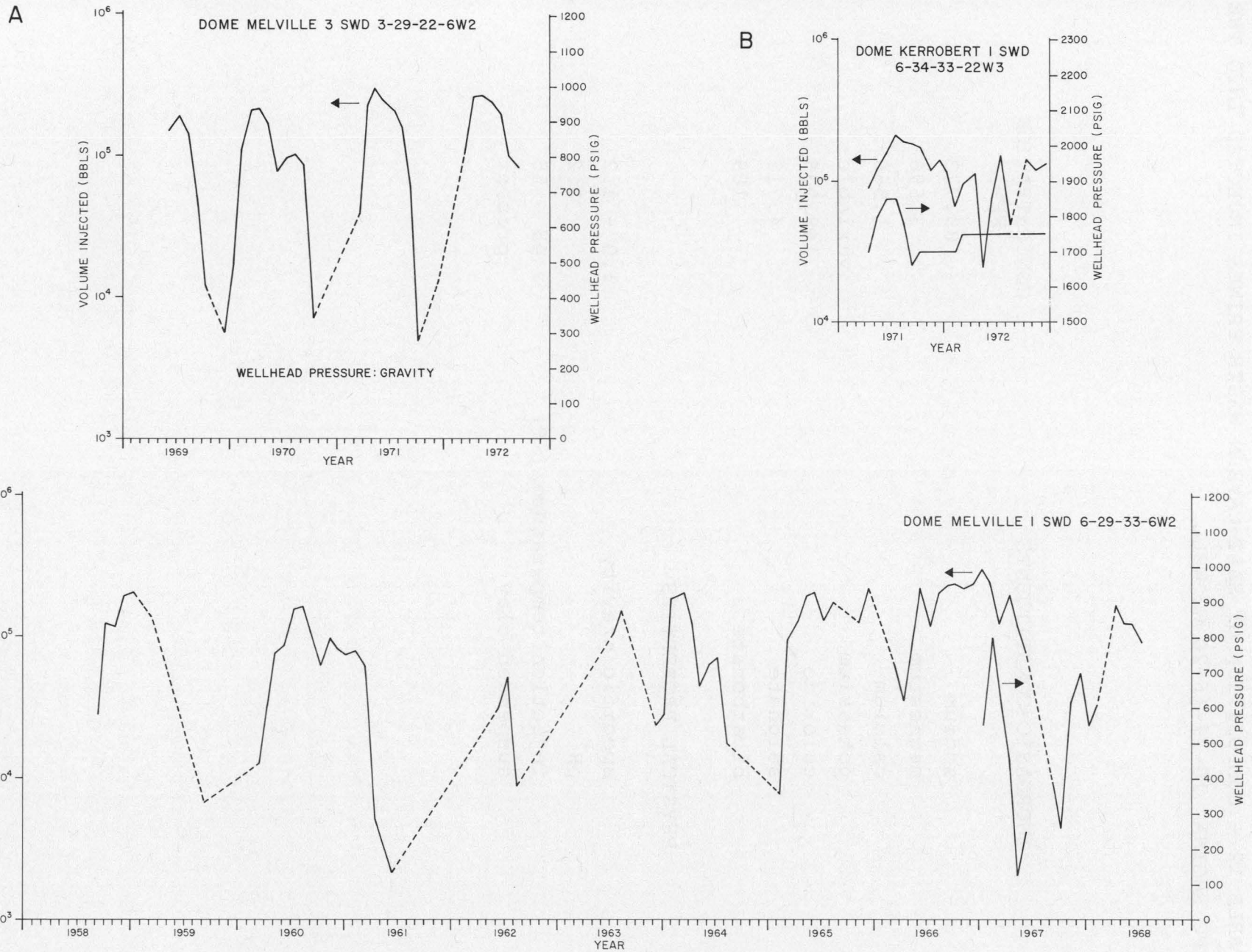
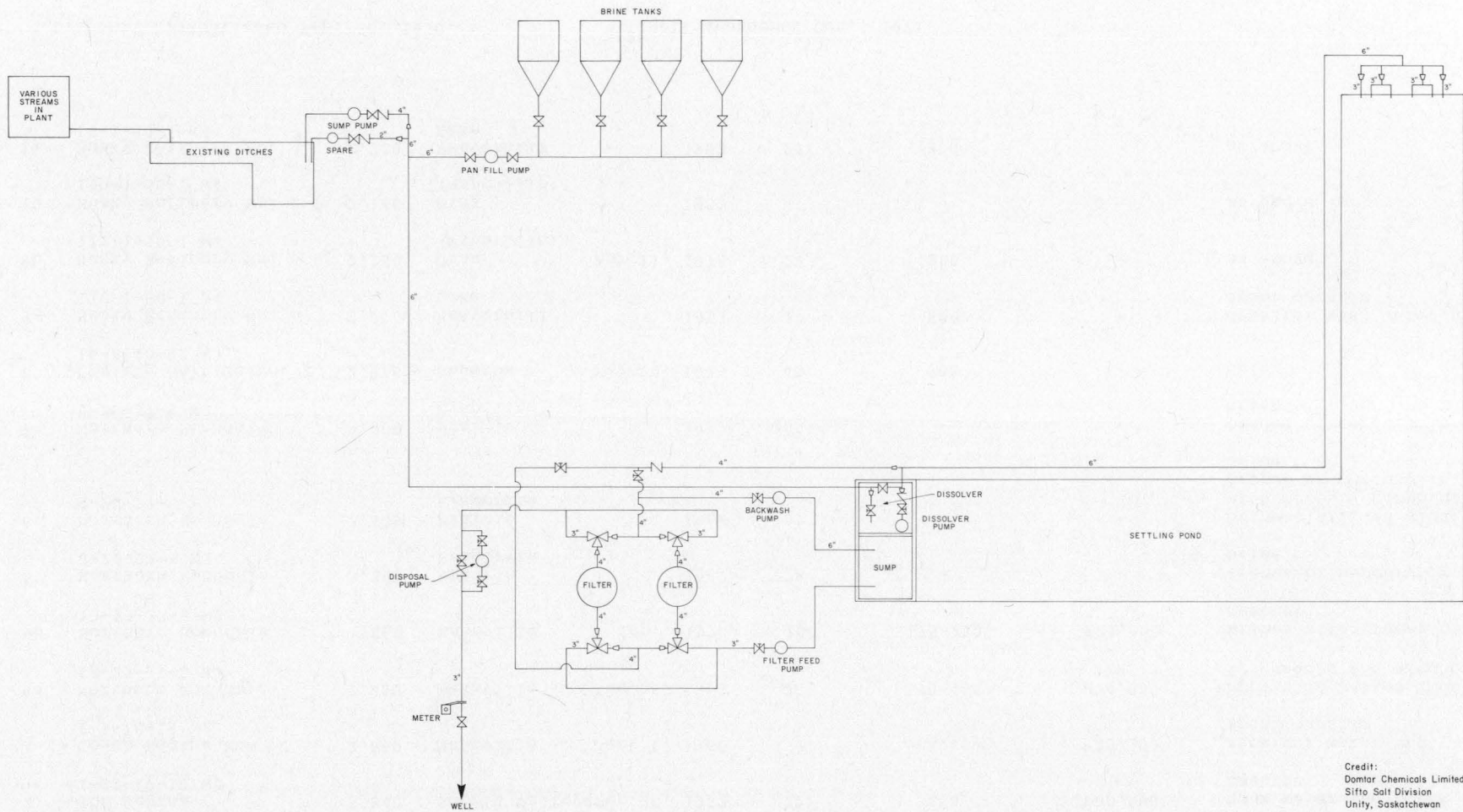


Fig. 27 — Operation histories of salt-cavern subsurface-disposal systems in Saskatchewan as time series of monthly average injection rates and pressures.

TABLE 12 - COMPOSITION OF SALT-CAVERN WASTE BRINES INJECTED INTO THE
 SPC REGINA 10-27-16-20 W2 WELL

INORGANIC CONSTITUENTS	CONCENTRATION (PPM)
sodium	89,723
magnesium	3,596
calcium	1,560
potassium	variable
chloride	148,035
sulphate	4,712
bicarbonate	189
PHYSICAL PROPERTIES	
specific gravity	1.0 - 1.2
pH	8.2
injection temperature (°F)	45 - 55
suspended clay	present



Credit:
 Domtar Chemicals Limited
 Sifto Salt Division
 Unity, Saskatchewan

Fig. 28 — Flowsheet of surface equipment for pre-injection treatment of waste in a salt-cavern brine-disposal system.

TABLE 13 - SUBSURFACE FLUID INJECTION SYSTEMS IN THE NORTHERN WILLISTON BASIN REGION: REFINERY AND CHEMICAL PLANT WASTE DISPOSAL

REF. NO.	DISPOSAL WELL	TOP OF DISPOSAL INTERVAL (Ft)	DISPOSAL FORMATION	DATE FIRST INJECTION	INJECTION RATE (US g/m)	INJECTION PRESSURE (psig)	TOT.CUM.VOL. INJECTED TO END 1972 (bbls)	WASTE CATEGORY
1	Imperial Virden 7-8-10-26 W1	2,100	Souris Valley	Jun., 1969	4	gravity	27,000	spent caustic
2	IOE Regina 4-32-17-19 W2	3,840	Souris Valley	Sep.26, 1963	22	350	2,600,000	sour water and spent caustic
3	Co-op Regina WDW 1-5-18-19 W2	2,690	Mannville	Jun. 1, 1966	3	gravity	930,000	receiver water and spent caustic
4a	Northern Rochdale 13-23-37-5 W3	1,860	Mannville	Aug. 6, 1963	20	150-400	874,000 ¹	herbicide wastes (mostly phenols and alcohols)
4b	Northern Rochdale 13-23-37-5 W3	1,860	Mannville	Sep., 1970	20	175-250	221,000	brines with traces of mercury
5	Northern Rochdale 3-26-37-5 W3	3,361	Prairie Evaporite	1967	228 ³	-	-	traces of mercury in brine
6	Northern Rochdale 4-26-37-5 W3	3,409	Prairie Evaporite	1962	57 ³	-	-	brine clarified sludge with mercury compounds; traces of mercury in brine
7	Northern Rochdale 5-26-37-5 W3	3,358	Prairie Evaporite	1967	285 ³	-	-	traces of mercury in brine
8	Prairie Salt Co.No. 2 15-4-40-22 W3	2,816	Duperow	May 24, 1973	40	700	-	brine
9a	Husky Refinery No. 5 11C-1-50-1 W4	2,770	Beaverhill Lake	1953	27	800	-	desalter wash water and spent caustic
9b	Husky Refinery No. 5 11C-1-50-1 W4	2,250	Dina (Mannville)	Apr.11, 1973	27	1,200	-	as above
10	Husky Refinery No. 2 ² 11D-1-50-1 W4	2,140	Dina (Mannville)	1951	-	-	-	as above
11	Husky Refinery No. 3 14-1-50-1 W4	2,730	Beaverhill Lake	1952	27	800	-	as above

¹ Disposal discontinued Sep. 30, 1970.

² Well abandoned Oct., 1971.

³ Approximate salt-cavern brining rates. Mercury compounds both present in solution or suspension and precipitated from downwell brine.

TABLE 14 - COMPOSITION OF REFINERY WASTE INJECTED INTO THE IOE REGINA
4-32-17-19 W2 WELL

ORGANIC CONSTITUENTS	CONCENTRATION (PPM)
SOUR WATER	
phenol	28
SPENT CAUSTIC	
phenol	2,250
 INORGANIC CONSTITUENTS	
SOUR WATER	
carbonate	17,550
sulphide	1,834
nitrogen	1,542
cyanide	52
SPENT CAUSTIC	
hydroxide	61,340
cyanide	10,452
carbonate	7,930
mercaptan	3,673
sulphide	656
sulphate	18
 PHYSICAL PROPERTIES	
SOUR WATER	
similar to those of water	
SPENT CAUSTIC	
specific gravity	1.2
viscosity (cp @ 100°F)	1.9
INJECTION STREAM	
pH	8.2
injection temperature (F)	90
suspended matter (ppm)	80

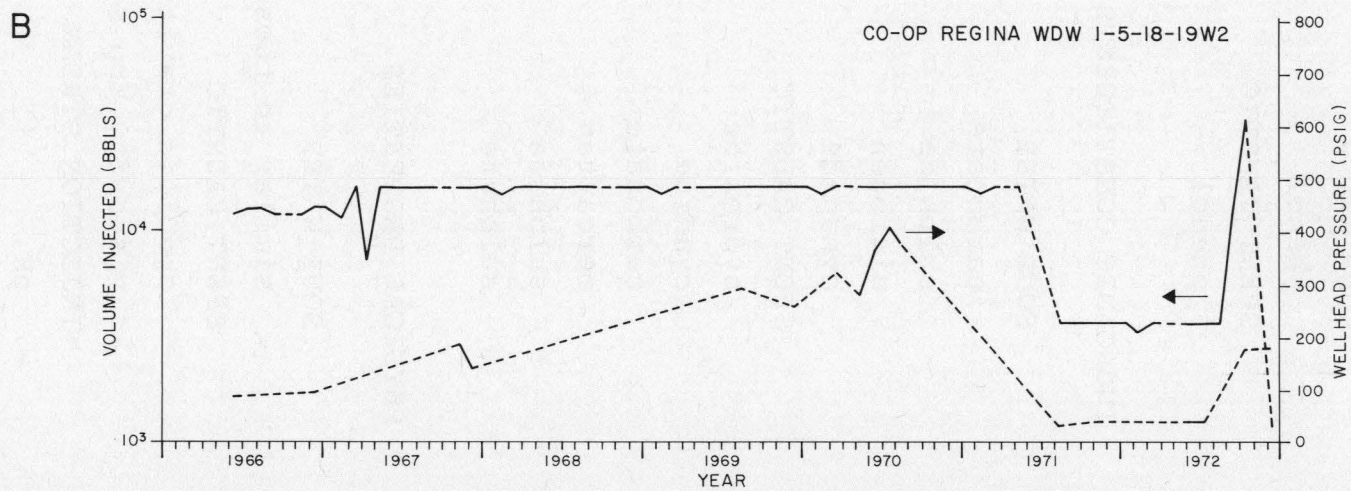
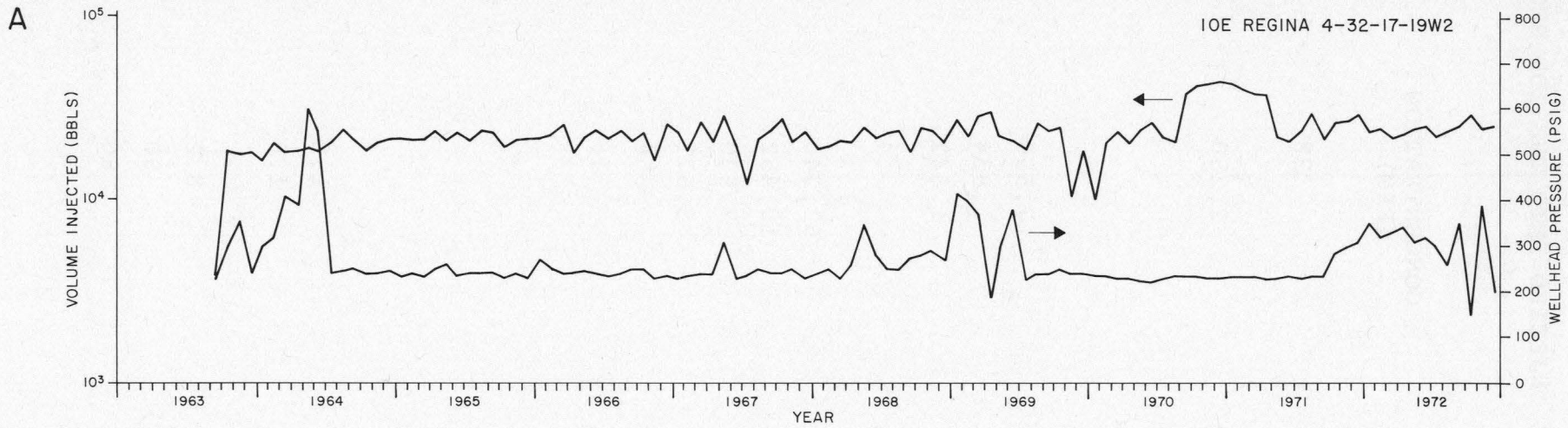
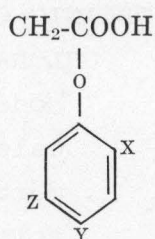


Fig. 29 — Operation histories of refinery subsurface-disposal systems in Saskatchewan as time series of monthly average injection rates and pressures.

Wastes generated during production of the herbicides 2,4-dichlorophenoxyacetic acid (2,4-D) and subordinately during 1969, 2-Methyl-4-chlorophenoxyacetic acid (MCPA) were injected into the lowermost part of the upper clastic division near Saskatoon from 1963 until the herbicide plant was shut down in 1970. These herbicides are chlorine-substituted phenoxyacetic acids with the structure where X, Y = Cl and Z = H in 2,4-D and X = CH₃, Y = Cl and Z = H in MCPA. Degradation of these compounds is dis-



cussed by Loos (1969). The wastes were neutralized phenolic brines with traces of 2,4-D, (Table 15) alcohols, esters and glycolic acid. Chlorinated derivatives of orthocresol, toluene, dimethylamine and various alcohols were injected during 1969. Since September, 1970, the same well has been used for disposal of waste brines with traces of mercury (1 to 50 ppm; average value 5 ppm), generated by a chlor-alkali plant. Injection rates have been low (20 U.S. g/m) and injection pressures moderate (150 to 400 psig). In addition, mercury compounds have been permitted to accumulate in each of three caverns in halite of the Prairie Evaporite, used to provide sodium chloride for the chlor-alkali plant. Records of injection are poor and the total cumulative volumes given are regarded as minimal values. Fig. 30 outlines the injection history of the Saskatoon chlor-alkali-plant disposal system. Average daily mercury content of injected brines in this system from June 1 to August 31 inclusive, 1973, is shown in Fig. 31.

Also included in this waste category is injection of "natural" brines into the upper part of the carbonate-evaporite division by Domtar Chemicals, Ltd., at Unity, which is closely comparable to disposal situations associated with salt-cavern solution facilities for underground gas storage.

PERSPECTIVES ON SUBSURFACE DISPOSAL IN SASKATCHEWAN

Volumes of injected fluid by waste category are related to stratigraphic position of the disposal formations and presented as proportions of the total injected fluid in Tables 16 and 17

respectively. The upper clastic division receives about 42 per cent of all injected fluids, whereas the carbonate-evaporite and basal clastic divisions receive of the order of 57.15 per cent and 0.85 per cent respectively. However, if oilfield injection systems are not taken into consideration, the upper clastic division is seen to receive 25.62 per cent of the fluid wastes (30,485,000 bbls), the carbonate-evaporite division 55.87 per cent (66,480,000 bbls) and the basal clastic division 18.51 per cent (22,030,000 bbls). The percentage given for the carbonate-evaporite division is no doubt too high and that for the basal clastic division too low by a corresponding amount, on account of uncertainties relating to multi-zone injection in four wells.

As is shown in Table 17, 96.11 per cent by volume of injected fluids, not associated with oilfield systems, are "natural" wastes, accounting for 23 of the 30 such disposal systems considered. This situation presents a marked contrast to subsurface waste disposal in both Ontario (McLean, 1968; Vonhof and van Everdingen, 1972) and Alberta (Vonhof and van Everdingen, *op. cit.*), which is almost entirely of "foreign" wastes. Thus, in most Saskatchewan subsurface disposal systems currently in operation, toxicity of waste is likely to be much less a problem in environmental-management uncertainty situations than consequences of high injection rates and high injection pressures. Such consequences might be accelerated lateral subsurface migration of waste fronts, vertical movement along fault planes and pressurization of superjacent strata. None of these possible effects has been recognized as such in Saskatchewan, although it should also be noted that at this time, there is no monitoring of waste migration by means of observation wells drilled to disposal formations. Monitoring of this type, in addition to wellhead records of flow rate and pressure, applied to mathematical models of subsurface flow, such as that of Freeze (1972), would render these models meaningful as prediction devices for particular real disposal situations.

A closely related problem is the need to reduce the amount of mercury in brines injected into the Mannville succession at the Saskatoon chlor-alkali plant, both from the standpoint of reducing pollution hazard to the environment and of increasing process efficiency. A treatment plant for the removal of mercury from the waste brines would cost in the order of \$300,000 (K. H. Lanouette, pers. comm. to Simpson), on the basis of comparison with a plant for the removal of iron from wastes recently set up by Industrial Pollution Control, Inc., of Connecticut.

TABLE 15 - COMPOSITION OF HERBICIDE AND CHLOR-ALKALI WASTES INJECTED INTO THE
NORTHERN ROCHDALE 13-23-37-5 W3 WELL

ORGANIC CONSTITUENTS

HERBICIDE WASTES

phenol
 p - chlorophenol
 o - chlorophenol
 2,4 - dichlorophenol
 2,6 - dichlorophenol
 2,4,6 - trichlorophenol
 2,4 - dichloroxyacetic acid
 o - cresol
 toluene
 di - methulamine
 n - butyl alcohol
 iso - butyl alcohol
 sec - butyl alcohol
 iso - propyl alcohol
 iso - octyl alcohol

INORGANIC CONSTITUENTS

CHLOR-ALKALI WASTES

sodium
 calcium
 mercury
 chloride
 carbonate
 sulphide

PHYSICAL PROPERTIES

HERBICIDE WASTES

specific gravity	1.1
pH	7-10
injection temperature (°F)	up to 100

CHLOR-ALKALI WASTES

pH	6 to 11
injection temperature (°F)	40 - 120

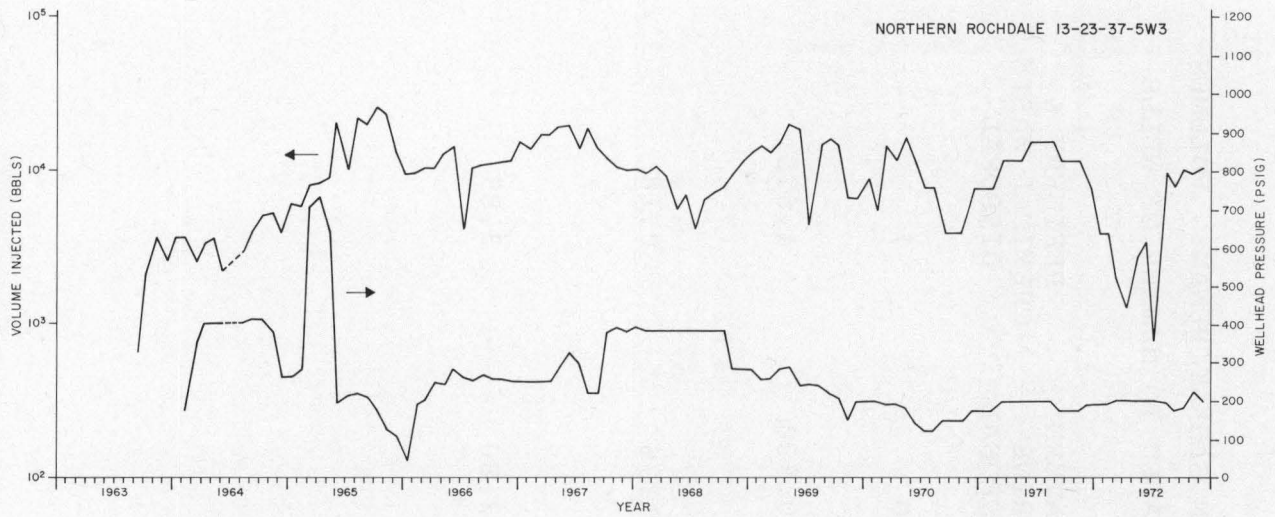


Fig. 30 — Operation history of Saskatoon chlor-alkali plant subsurface-disposal system as time series of monthly average injection rates and pressures.

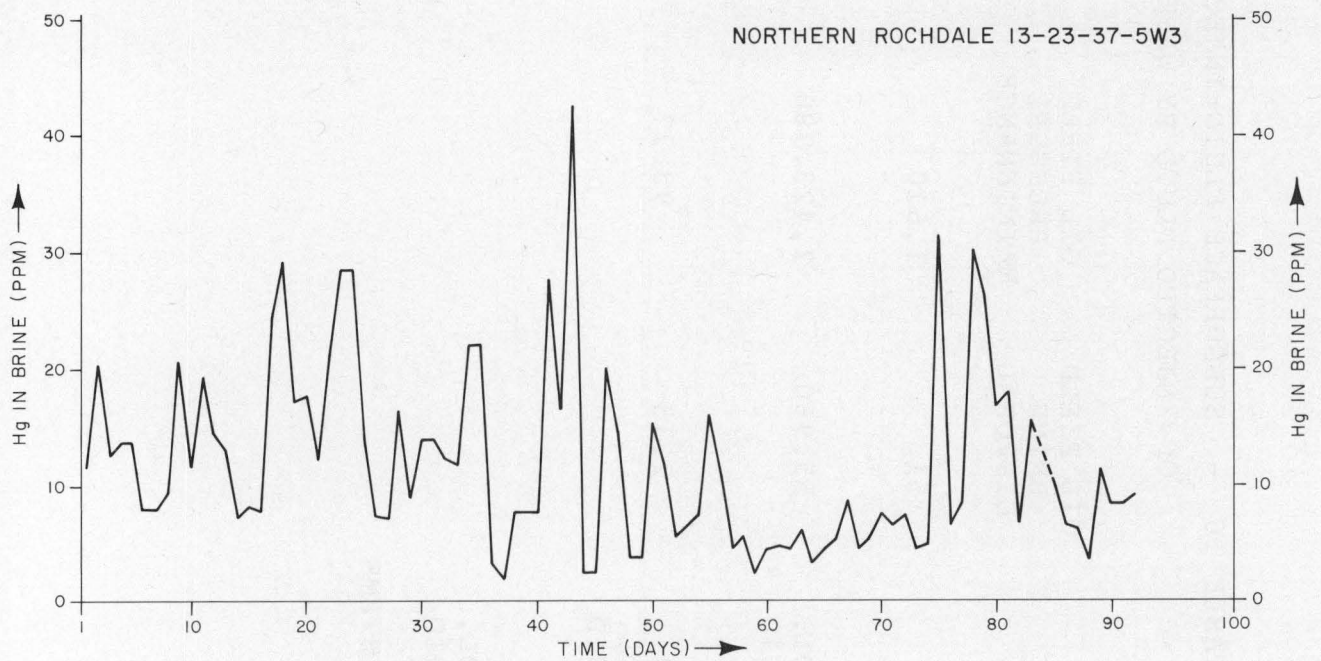


Fig. 31 — Time series of daily average proportions of mercury in brines for deep-well injection at Saskatoon chlor-alkali plant, June 1 to August 31 inclusive, 1973.

TABLE 16 - SUBSURFACE FLUID-INJECTION SYSTEMS IN SASKATCHEWAN: VOLUMES OF INJECTED FLUID BY WASTE CATEGORY RELATED TO NUMBER OF WELLS

	OIL FIELD BRINE DISPOSAL	OIL FIELD PRESSURE MAINTENANCE	POTASH BRINE DISPOSAL	CAVERN BRINE DISPOSAL	REFINERY & CHEMICAL WASTE DISPOSAL	TOTAL
TOT. NO. OF WELLS	51	1,610	13	10	7	1,691
TOT. CUM. VOL. INJECTED FLUID (MMbbls)	55.960	2,423.980	63.440	50.930	4.625	2,598.935
89 PERCENT OF TOT. CUM. VOL. INJECTED FLUID	2.15	93.27	2.44	1.96	0.18	100.00
PERCENT OF TOT. CUM. VOL. INJECTED FLUID EXCLUSIVE OF OIL FIELD SYSTEMS			53.31	42.80	3.89	100.00

TABLE 17 - SUBSURFACE FLUID-INJECTION SYSTEMS IN SASKATCHEWAN: VOLUMES OF INJECTED FLUIDS
BY WASTE CATEGORY AND LITHOSTRATIGRAPHIC DIVISION

LITHO- STRATIGRAPHIC DIVISION	WASTE CATEGORY	OIL FIELD BRINE DISPOSAL (bbls)	OIL FIELD PRESSURE MAINTENANCE (bbls)	POTASH BRINE DISPOSAL (bbls)	CAVERN BRINE DISPOSAL (bbls)	REFINERY & CHEMICAL WASTE DISPOSAL (bbls)	TOT. CUM. VOL. FLUID DISPOSED (bbls)
Upper Clastic Division		44,280,000	1,016,760,000	2,870,000	25,590,000	2,025,000	1,091,525,000
Carbonate-Evaporite Division		11,680,000	1,407,220,000	38,540,000 ¹	25,340,000	2,600,000	1,485,380,000
Lower Clastic Division		-	-	22,030,000	-	-	22,030,000
Entire Sedimentary Sequence		55,960,000	2,423,980,000	63,440,000	50,930,000	4,625,000	2,598,935,000

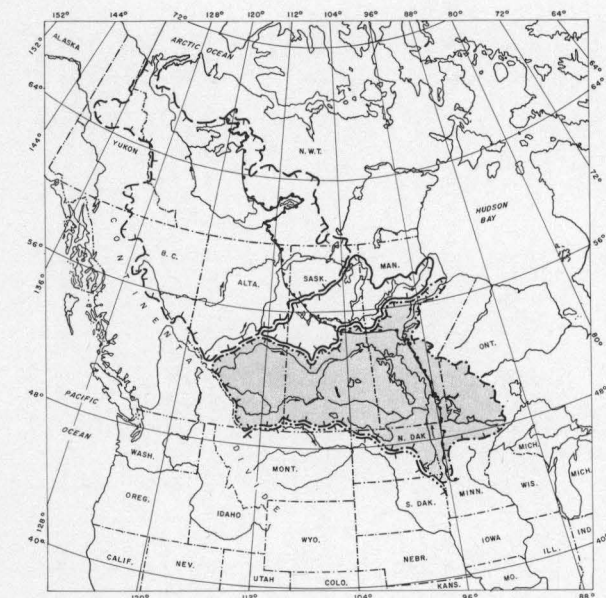
¹ Undetermined proportion of this volume injected into the lower clastic division in four multizone injection systems

SUBSURFACE WASTE DISPOSAL AND SURFACE WATERS

It is of interest to note that all subsurface waste disposal, exclusive of oilfield brine injection, in Saskatchewan (30 wells), Alberta (22

wells) and Manitoba (1 well) is presently located in the Saskatchewan-Nelson drainage basin (Fig. 32).

Thus failure of subsurface disposal systems in the area, resulting in pollution of surface waters may have serious interprovincial consequences.



A

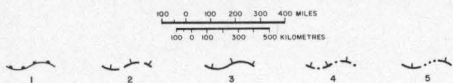


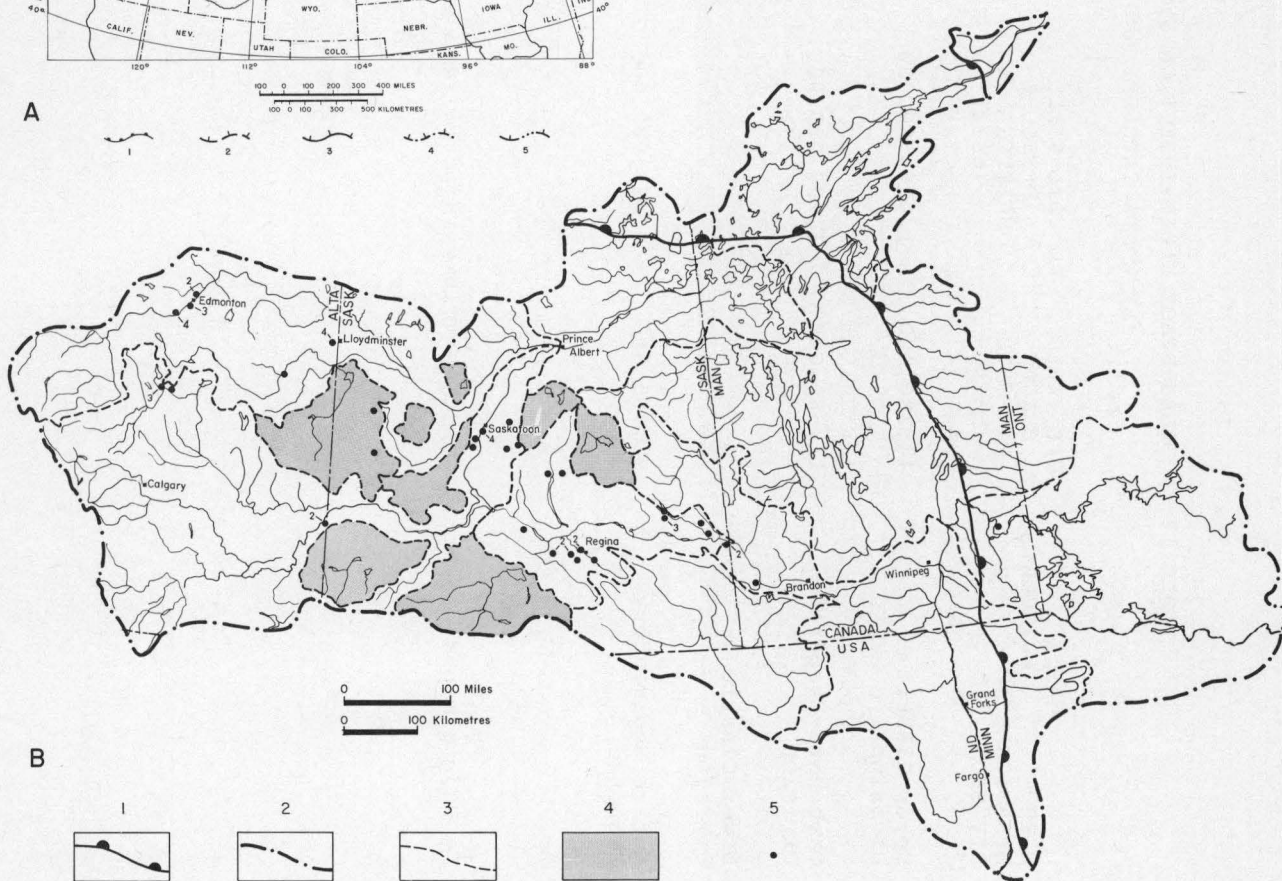
Fig. 32 — The Saskatchewan-Nelson drainage basin with distribution of deep-well disposal systems indicated.

A — Location map.

- 1 — perimeter of Precambrian Shield
- 2 — Peace-Athabasca basin
- 3 — Churchill basin
- 4 — Saskatchewan-Nelson basin
- 5 — Missouri basin

B — Saskatchewan-Nelson drainage basin, sub-basins and deep-well disposal systems.

- 1 — perimeter of Precambrian Shield
- 2 — major basin
- 3 — sub-basin
- 4 — internal drainage
- 5 — disposal wells



B



ECONOMIC FACTORS IN SUBSURFACE WASTE DISPOSAL

GENERAL STATEMENT

Casing and tubing strings and a generalized wellhead, used in a typical waste-disposal well, are shown schematically in Fig. 33. Types of disposal-well completion favoured in Saskatchewan are illustrated in Fig. 34. A multizone disposal system with a combination of two different completion types (perforations and screen; gravel pack) is shown schematically in Fig. 35.

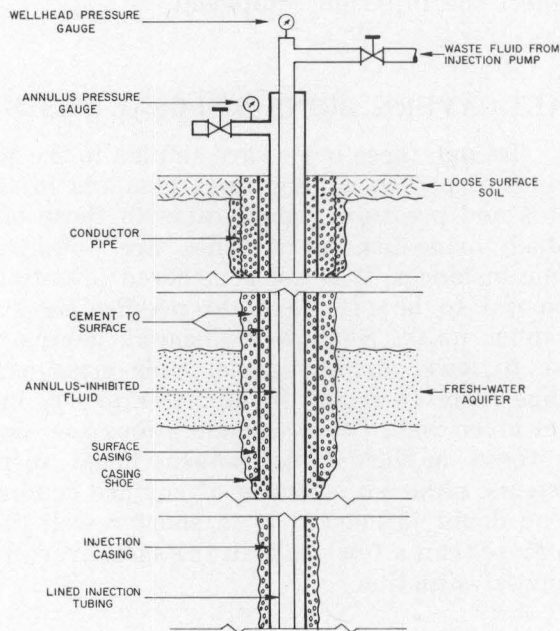


Fig. 33 — Typical casing strings and wellhead used in a waste-disposal well.

In Table 19, an attempt is made to summarize costs for Saskatchewan fluid-injection systems, currently in use, on the basis of data supplied by operators. Shortcomings of Table 19 are a few arguably unrepresentative costs which are either estimates based on incomplete records or costs of old wells, not valid by today's standards. Nevertheless, a largely consistent pattern of fund allocation emerges:

1. Oilfield brine injection wells, simple in design and drilled in producing districts, where the geology of the disposal formation is fairly well known, are the least costly systems.

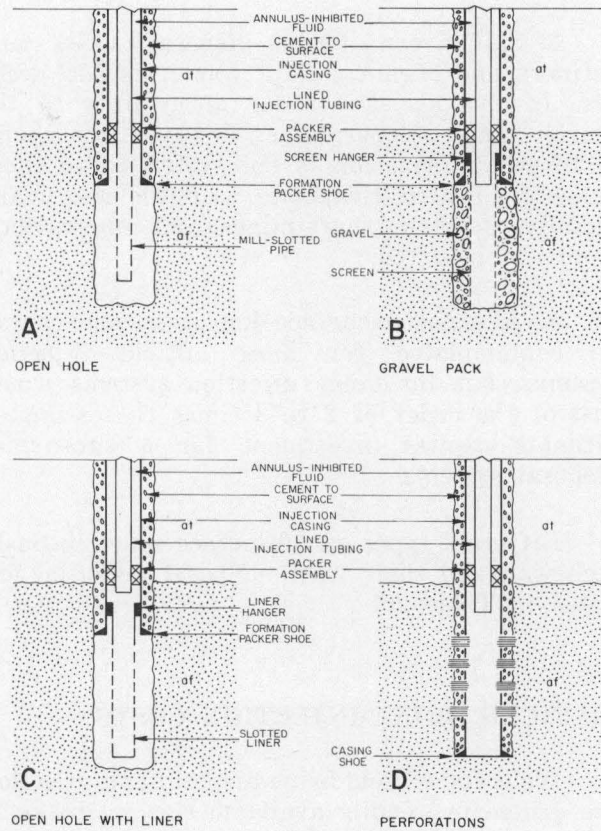


Fig. 34 — Options for disposal-well completion.

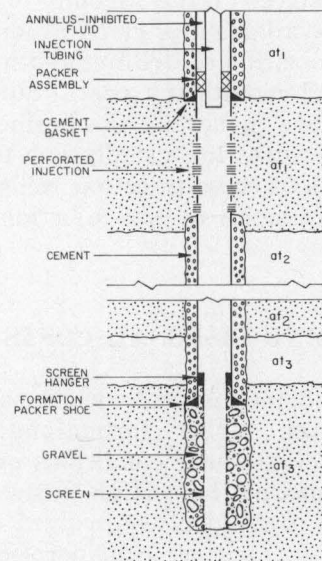


Fig. 35 — Multizone injection system with combination of perforations and screen plus gravel pack.

2. Potash brine disposal wells, more complex in design and frequently involving directional drilling to deep formations and testing in situations of uncertainty, are the most refined systems and the most costly.

3. Salt-cavern brine disposal wells and refinery and chemical-plant waste disposal wells also involve decision under uncertainty in the search phase of operations. However, the choice of disposal formation is not restricted to those below the Prairie Evaporite, as is the case in the vicinity of potash shaft mines, and intermediate costs are incurred.

4. Alternative surface disposal clearly cannot be contemplated for most oilfield injection systems, but for other injection systems would cost of the order of 2 to 3 times the estimated ultimate capital investment for a subsurface disposal system.

Different types of subsurface space in Saskatchewan and their waste-disposal potential are listed in Table 20.

OILFIELD BRINE-INJECTION COSTS

Wells for oilfield brine-disposal and injection are drilled by readily available rigs in districts, where the correlation surfaces and facies changes, which define the injection/producing unit, usually can be mapped with high degree of accuracy. Thus the relatively large amount of subsurface information available at a given production locale permits optimization of drilling and minimization of testing and monitoring costs. Surface equipment costs are generally low, since injection rates and pressures are usually low to moderate. Thus the costs of these injection wells are largely determined by depth of the injection formation.

POTASH BRINE-DISPOSAL COSTS

Potash brine-disposal wells are usually drilled to deep target formations below the Prairie Evaporite under conditions of paucity of subsurface information. High costs arise as a result of the great depths involved and related uncertainty, as well as considerations of well design, which must take into account high injection rates and pressures during a well life of 1 to 2 decades. Hole size may range from 17½ inches in diameter over the first 500 feet or so to 8¾

inches down to total depth in a given well and costs of casing (lined) and tubing strings and cementing the well to the surface from the disposal formation are correspondingly high. Mud programs must employ fluids, which do not react with evaporite minerals, but will not damage the target disposal formation. Directional drilling is carried out within and below the Prairie Evaporite to ensure the safety of mine workings. A comprehensive suite of geophysical well logs is run in each case and extensive testing is necessary to determine the best possible injection interval. High injection rates and pressures during operation necessitate high-capacity pumping equipment and monitoring facilities, which will permit continuous measurement of both low and high pressure values to protect the injection equipment.

SALT-CAVERN BRINE-DISPOSAL COSTS

Though these brines are similar to the waste brines of potash mining operations and injection rates and pressures, comparable to those of the potash brine-disposal systems, are obtained in some instances, it is not considered essential for disposal to be effected into pre-Prairie stratigraphic units. Shallower disposal depths give rise to lower drilling costs. Hole sizes usually range from 15 inches in diameter to 8¾ inches in a given well. Other considerations are similar to those applicable to potash brine disposal systems, although selection of surface equipment is no doubt influenced by a shorter well life of no more than a few years in the salt-cavern brine disposal situation.

REFINERY AND CHEMICAL-PLANT WASTE-DISPOSAL COSTS

With the exception of the Domtar brine-disposal system, which is similar to the salt-cavern disposal systems outlined above, these industrial waste-disposal wells have been in use for 10 years and the costs given cannot be readily compared with those of the newer systems. Drilling and completion procedures were the same as those adopted for oilfield brine-disposal systems, though additional testing in the systems considered reflects both the low level of existing information on the geological setting and the need for compatibility between "foreign" wastes and formation fluids. Pumping equipment is similar to that in oilfield systems, because of the fairly low injection rates and volumes.

TABLE 18 - WELL-COMPLETION OPTIONS FOR DIFFERENT TYPES OF
SUBSURFACE WASTE-DISPOSAL SYSTEMS IN SASKATCHEWAN

COMPLETION OPTION	POTASH ¹	SALT-CAVERN	REFINERY & CHEMICAL-PLANT
OPEN HOLE	1	5	2
GRAVEL PACK	(4)	0	0
OPEN HOLE WITH LINER	1	4	0
PERFORATIONS	2 +(4)	1	2
MULTIZONE	4	0	0
CAVERN DISPOSAL	0	0	3

¹ Bracketted values relate to multizone completions

TABLE 19 - CAPITAL EXPENDITURE IN DOLLARS ¹ FOR DIFFERENT TYPES OF SUBSURFACE WASTE-DISPOSAL SYSTEM IN SASKATCHEWAN

COST ITEM	OILFIELD	POTASH	SALT CAVERN	REFINERY & CHEMICAL PLANT
DRILLING	5,000 - 45,000	70,000 - 100,000 87,333 (6)	30,000 - 38,000 34,750 (4)	0 - 58,000 43,000 (2)
COMPLETION	1,000 - 8,000	57,000 - 137,000 89,000 (7)		-
CASING	6,000 - 27,000		18,000 - 27,100 21,525 (4)	16,000 - 22,000 19,667 (3)
DRILLING, CASING & COMPLETION PER FT.	8.00 - 12.00	23.04 - 49.83	14.57 - 21.16	-
TESTING	0 - 5,000	1,800 - 18,200 11,357 (7)	1,000 - 2,000 1,533 (3)	2,000 - 5,000 3,500 (2)
PUMPS & SURFACE FACILITIES	0 - 150,000	5,500 - 215,000 79,685 (7)	20,000 - 250,000 98,000 (3)	4,000 - 111,000 42,333 (3)
INJECTION PER 1000 GALLONS EFFLUENT	-	0.10 - 0.15	0.16 - 0.29	-
MONITORING	0 - 1,000	3,000 - 11,200	1,000 (2)	negligible - 5,000
YEARLY OPERATING & MAINTENANCE	1,000	6,000 - 86,700 34,583 (6)	13,000 - 21,000 16,833 (3)	negligible - 4,100
ULTIMATE CAPITAL INVESTMENT PER WELL	37,000 - 157,000	120,000 - 418,000 291,625 (8)	25,657 - 321,700 100,606 (7)	95,000 - 134,000 110,000 (3)
ALTERNATIVE SURFACE DISPOSAL	N/A	178,000 - 750,000 407,000 (4)	500,000 - 1,000,000 666,667 (3)	10,000 - 250,000 130,000 (2)

¹ Range and arithmetic mean given where possible.
Figures in brackets indicate number of averaged values in each case.

TABLE 20 - WASTE-DISPOSAL POTENTIAL OF DIFFERENT TYPES OF
SUBSURFACE SPACE IN SASKATCHEWAN

SUBSURFACE SPACE CATEGORY	STRATIGRAPHIC DISTRIBUTION	RECOMMENDED UNDERGROUND WASTE MANAGEMENT STATUS	WASTE CATEGORIES FOR UNDERGROUND DISPOSAL	OPTIMUM DISPOSAL-SITE LOCATION	REMARKS
1. intergranular porosity	upper clastic division lower clastic division	restriction to oil-field systems high potential	"natural" wastes at low pressure and low injection rate "natural" wastes and nonradioactive, "foreign" wastes	hydrocarbon-producing locales stratigraphic-trap situations with subdued structure	lower clastic division likely to be increasingly used by potash industry, observation wells needed
2. carbonate porosity types	basal part of upper clastic division carbonate-evaporite division	restriction to oil-field systems pre-Prairie units of high potential; post-Prairie units with restriction to "natural" wastes	"natural" wastes only	hydrocarbon-producing locales	carbonate-evaporite division with good potential for continued disposal of salt-cavern and potash-mine brines, observation wells needed
3. solution breccias	post-Prairie strata in carbonate-evaporite division	potential generally low	—	—	rocks poorly known, but low porosities and permeabilities and frequent association with vertical fractures render them largely unsuitable to receive fluid wastes
4. hydraulically induced fractures in shales	upper clastic division lower clastic division	unsuitable for permanent systems; experimentation with brines admissible high potential, but experimentation necessary	none admissible for permanent systems "foreign" nonradioactive and low-level, radioactive wastes	— thickest shale sections	experimentation on fracturing and grouting necessary; observation wells needed
5. excavations in igneous and metamorphic rocks	basement	high potential	low to high-level radioactive wastes in metal and/or concrete containers only	central Saskatchewan where Phanerozoic cover thin; Shield area exclusive of the Athabasca basin region	only unfractured basement rocks may be considered for disposal; continuous monitoring necessary
6. potash	Prairie Evaporite of carbonate-evaporite division	high potential	low to high-level radioactive wastes in metal and/or concrete containers only	current potash-production locales	continuous monitoring necessary
7. caverns from controlled solution of evaporite strata	carbonate-evaporite division	high potential	low to high-level radioactive wastes in metal and/or concrete containers necessary	current potash-production locales	continuous monitoring necessary

COST ESTIMATES OF SUBSURFACE AND SURFACE DISPOSAL SYSTEMS COMPARED

Surface storage of the enormous volumes of waste brines, generated at high rates over long time periods by the potash industry and over much shorter time periods by salt-cavern operations, would be at least 2 to 3 times more costly than subsurface waste disposal for the operators and would also result in loss of wide areas of farm land over periods of many years. Lagoons and natural depressions currently in use by operators are in most cases located near major, undeveloped, fresh-water aquifer systems in glacial deposits (Vanhof, in press) and this potential hazard to future water resources would be greatly increased in the absence of subsurface disposal facilities. The authors consider the cost-estimate range given in Table 19 for surface disposal of salt-cavern brines to be excessively high; the potash brine estimates are likely to be more applicable for both waste categories. The volumes of refinery and chemical-plant wastes currently produced are small by comparison with the amount of "natural" brines injected into subsurface aquifers, but subsurface disposal is considerably less costly than surface storage in all cases but one. In all cases, the effects of waste injection into confined, subsurface aquifers, in

terms of rate of waste migration and local modification of fluid-potential distribution will only be adequately assessed when observation wells are drilled to the disposal formations.

UTILIZATION OF INDUSTRIAL WASTES

Sodium chloride from the waste brines, produced by the potash solution-mining operation of Kalium Chemicals, Ltd., at Belle Plaine, is utilized at a \$3-million plant owned by the Canadian Salt Company. This plant has been in operation since 1970 and makes 165 salt products. It has a capacity to produce 200,000 tons of salt annually. It is unfortunate that the market for sodium chloride is such that more plants to process potash-mine and salt-cavern waste brines could not be made economically viable.

Chemicals potentially useful to a number of industries are produced as waste effluent by Saskatchewan refineries. For example, hydrogen sulphide from refinery sour water could be supplied to a sulphur plant, but is produced in quantities too small to be so utilized. Likewise, refinery spent caustic might serve the pulp and paper industry, but for the small volume.

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APPENDIX I

QUESTIONNAIRE ON SUBSURFACE WASTE-DISPOSAL OPERATIONS IN SASKATCHEWAN

Subject

.....

.....

Company

.....

.....

Representative

.....

.....

Interviewed by

Place

Date

1. WASTE CHARACTERISTICS

- 1.1 Chemical composition and concentration of all constituents
- 1.2 Physical properties of all constituents
- 1.3 Stability in subsurface environment (reactions between constituents under new temperature, pressure conditions; reactions between waste and host rock, formation fluids; etc.)
- 1.4 Estimated production rate and total volume by constituent
- 1.5 Potential for recycling and re-use of part of waste
- 1.6 Does the waste require special treatment prior to injection? (affecting compatibility with subsurface environment, etc.)
- 1.7 Are there any special difficulties in handling the waste?
- 1.8 Could the volume of waste or number of waste constituents be reduced by alternative technology operations?

2. SELECTION OF SITE AND FORMATION

- 2.1 What were the most important factors determining selection of the disposal site?
- 2.2 To what extent were cores, geophysical logs, drill-stem tests, core analyses and fluid analyses utilized?
- 2.3 How was the disposal formation selected?
- 2.4 Were alternative disposal formations considered?
- 2.5 At what level of information were disposal operations begun?

3. DRILLING AND COMPLETION OF INJECTION WELL

- 3.1 What drilling procedure was adopted?
- 3.2 What drilling problems were encountered and how were they remedied?
- 3.3 What well design was favoured?
- 3.4 Was experimentation with different well designs carried out?
- 3.5 What completion problems were encountered and how were they remedied?
- 3.6 Are there instances of changes in well design being effected after a period of operation?

- 3.7 If abandonment of disposal wells has been effected by your company, why and by what procedure? Any improvements on generally accepted practice?
- 3.8 What surface installations are required?
- 3.9 What is present capacity of pumping and well equipment and do you anticipate a change of equipment in the future?

4. TESTING OF INJECTION WELL AND DISPOSAL FORMATION

- 4.1 What results were obtained from water-injection tests?
- 4.2 What results were obtained from waste-injection tests?
- 4.3 If the disposal formation was fractured, what effects were noted in the confining beds?
- 4.4 What other tests were performed to evaluate the disposal formation?

5. MONITORING OF OPERATIONS

- 5.1 What is the nature of the monitoring system?
- 5.2 What results have been obtained from drilling of observation wells?
- 5.3 Have fresh-water horizons near the disposal well and around the nearest abandoned holes been sampled?
- 5.4 Are there other monitoring systems that you may have considered for your disposal wells?

6. OPERATIONAL SAFEGUARDS

- 6.1 Does the injection-pressure monitor have an alarm system?
- 6.2 Are emergency storage facilities available?
- 6.3 What steps have been taken regarding waste disposal after shutdown or failure of the subsurface-disposal facility?
- 6.4 How are surface installations isolated from surface-water or ground-water resources?
- 6.5 What steps are being taken to safeguard downhole equipment?
What steps are being taken to monitor this equipment?

7. ECONOMICS OF WASTE DISPOSAL

- 7.1 Costs of

(a) acquisition	(g) operation
(b) drilling	(h) monitoring
(c) testing	(i) hiring of geologists and engineers for design and completion of the disposal system
(d) casing	(j) other (development)
(e) pumping equipment	(k) abandonment
(f) waste-treating facilities	
- 7.2 Ultimate capital investment estimated per disposal well.
- 7.3 Estimated costs of alternative surface disposal (storage)

8. WASTE MANAGEMENT

- 8.1 What do you consider to be the most urgently needed regulations for control of subsurface waste disposal?
- 8.2 Which areas of research into the processes involved in subsurface waste disposal do you consider to be in need of immediate study?

APPENDIX II

GROUND WATER USE PROJECTS
FROM BEDROCK AQUIFERS

File	Owner	Location	Source*	Purpose	Depth	Annual Allocation Acre-Feet	Diversion Rate ig/m	Year Installed or Put to Use
25	Dairy Producers	SW 17- 8-18-W3	22	Ind.	100	5	10	1948
33	Dairy Producers	SW 33-36- 5-W3	25	Ind.	260	48	50	1957
46	Assiniboia T.	SW 23- 7- 1-W3	30	Mun.	61	110	100	1959
56	Domtar	SE 9-40-22-W3	30	Ind.	151	90	50	1960
57	Macklin Town	SE 10-39-28-W3	30	Mun.	256	40	25	1960
58	Domtar	NE 4-40-22-W3	30	Ind.	190	110	65	1960
67	Macklin Town	NE 3-39-28-W3	30	Mun.	240	10	15	1960
79	Herschel V.	SW 9-31-17-W3	30	Mun.	240	10	10	1961
74	Domtar	NE 4-40-22-W3	30	Ind.	200	50	30	1960
114	Lashburn V.	SE 8-48-25-W3	26	Mun.	132	25	20	1962
127	Sceptre V.	NE 9-22-24-W3	30	Mun.	192	25	25	1963
148	Dairy Producers	SW 4-37- 5-W3	25	Ind.	195	25	30	1963
155	Doddsland V.	SW 6-33-20-W3	25	Mun.	235	40	20	1963
242	Tramping Lake V.	SW 33-36-21-W3	25	Mun.	265	25	20	1963
251	Primate V.	SE 17-38-27-W3	25	Mun.	252	10	15	1966
280	Paynton V.	NE 35-46- 2-W3	26	Mun.	130	20	20	1966
328	Evesham V.	SE 32-39-27-W3	40	Mun.	220	8	7	1967
330	Viceroy V.	NE 12- 6-26-W2	22	Mun.	317	15	9	1967
345	Rush Lake V.	NW 1-17-11-W3	30	Mun.	352	14	7	1968
353	Laporte H.	SW 13-26-26-W3	25	Mun.	350	10	8	1966
361	Bienfait T.	SW 19- 2- 6-W2	22	Mun.	110	40	30	1957
362	Bienfait T.	SW 19- 2- 6-W2	22	Mun.	114	40	30	1962
363	Bienfait T.	SW 19- 2- 6-W2	22	Mun.	117	30	20	1963
364	Strongfield V.	NE 26-27- 5-W3	25	Mun.	525	12	12	1967
382	Central Butte T.	SW 21-21- 4-W3	24	Mun.	480	35	40	1963
397	Manalta Coal	SE 21- 2- 7-W2	22	Ind.	174	3	5	1960
398	Manalta Coal	SE 4- 2- 7-W2	22	Ind.	406	3	5	1962
399	Man. & Sask. Coal	NW 3- 2- 6-W2	22	Ind.	177	15	10	1946
400	Man. & Sask. Coal	NW 3- 2- 6-W2	22	Ind.	180	10	6	1961
401	Man. & Sask. Coal	NW 3- 2- 6-W2	22	Ind.	161	15	10	1961
426	Loreburn V.	SE 23-26- 5-W3	25	Mun.	565	26	18	1962
427	Hanley T.	NW 1-31- 4-W3	25	Mun.	300	30	25	1961
428	Hanley T.	NE 1-31- 4-W3	25	Mun.	330	15	12	1962
435	Sybouts Sodium	NW 14- 1-19-W2	22	Min. Rec	57	27	15	1958
436	Sybouts Sodium	NW 14- 1-19-W2	22	Min. Rec	57	48	25	1958
435	Sybouts Sodium	NW 14- 1-19-W2	22	Min. Rec	57	48	25	1958
444	Milden V.	NW 17-29-11-W3	25	Mun.	420	25	25	1959
468	Minton V.	SW 35- 2-20-W2	30	Mun.	48	20	15	1964
470	Willow Bunch T.	SW 17- 5-27-W2	30	Mun.	39	—	18	1964
478	Carievale V.	NW 31- 2-31-W1	22	Mun.	206	25	20	1904
429	Lampmont	SW 16- 5- 6-W2	22	Mun.	278	100	60	1966
490	Beechy V.	NW 18-22-10-W3	25	Mun.	356	—	10	1961
491	Beechy V.	NW 18-22-10-W3	25	Mun.	230	—	7	1963
492	Beechy V.	SW 19-22-10-W3	25	Mun.	232	—	6	1966
493	Beechy V.	SW 19-22-10-W3	25	Mun.	228	—	20	1968
551	Kerrobot T.	NW 13-34-23-W3	25	Mun.	300	90	50	1972
552	Ormiston M&S	NW 9- 9-25-W2	22	Min. Rec	67	—	38	1967
553	Ormiston M&S	SW 16- 9-25-W2	22	Min. Rec	90	—	150	1967
554	Ormiston M&S	SW 16- 9-25-W2	22	Min. Rec	90	—	50	1967
555	Ormiston M&S	NW 16- 9-25-W2	22	Min. Rec	104	—	12	1967

*Source	Code	*Source	Code	*Source	Code
Cypress Hills	21	Judith River	25	Blairmore	29
Ravenscrag	22	Ribstone Creek	26	Other Bedrock	30
Eastend	23	Lea Park	27	Undetermined	40
Bearpaw	24	Viking	28		

File	Owner	Location	Source*	Purpose	Depth	Annual Allocation Acre-Feet	Diversion Rate ig/m	Year Installed or Put to Use
556	Ormiston M&S	NW 16- 9-25-W2	22	Min. Rec	130	—	14	1967
557	Ormiston M&S	SW 21- 9-25-W2	22	Min. Rec	143	—	11	1967
558	Ormiston M&S	SE 20- 9-25-W2	22	Min. Rec	185	—	16	1967
559	Ormiston M&S	SE 20- 9-25-W2	22	Min. Rec	127	—	16	1967
560	Gladmar V.	SE 34- 2-19-W2	22	Mun.	159	15	15	1967
574	Denzil V.	NE 33-37-26-W3	25	Mun.	226	30	30	1965
576	Shaunavon T.	NE 17- 8-18-W3	22	Mun.	101	—	30	1961
577	Shaunavon T.	NW 17- 8-18-W3	22	Mun.	100	—	75	1964
578	Shaunavon T.	SW 17- 8-18-W3	22	Mun.	100	—	75	1962
583	Torquay V.	NW 24- 2-12-W2	22	Mun.	150	20	20	1962
584	Torquay V.	NW 24- 2-12-W3	22	Mun.	155	25	25	1962
588	Willow Bunch T.	SE 24- 5-28-W2	22	Mun.	10	23	12	1939
590	Luseland T.	NE 8-36-24-W2	25	Mun.	527	30	20	1968
591	Sybouts Sod. Sul.	NE 14- 1-19-W2	22	Min. Rec	58	—	150	1969
592	Sybouts Sod. Sul.	NE 14- 1-19-W2	22	Min. Rec	47	—	150	1969
593	Sybouts Sod. Sul.	NE 14- 1-19-W2	22	Min. Rec	66	—	250	1969
594	Sybouts Sod. Sul.	NE 14- 1-19-W2	22	Min. Rec	42	—	150	1969
595	Sybouts Sod. Sul.	NE 14- 1-19-W2	22	Min. Rec	60	—	150	1969
596	Sybouts Sod. Sul.	NE 14- 1-19-W2	22	Min. Rec	37	—	150	1969
597	Sybouts Sod. Sul.	NE 14- 1-19-W2	22	Min. Rec	53	—	150	1969
601	Marshall V.	SW 5-49-26-W3	26	Mun.	164	10	10	1950
603	Marshall V.	SW 5-49-26-W3	26	Mun.	156	15	10	1967
606	Ormiston M & S	SW 16- 9-25-W2	22	Min. Rec	93	—	60	1968
607	Ormiston M & S	NW 9- 9-25-W2	22	Min. Rec	142	—	20	1968
649	Herschel V.	SW 9-31-17-W3	25	Mun.	180	—	5	1970
653	Senlac V.	NE 32-40-26-W3	25	Mun.	—	—	6	—
676	Hawarden V.	NE 26-28- 5-W3	25	Mun.	600	—	—	1964
692	Lashburn V.	SE 8-48-25-W3	26	Mun.	134	25	20	1968
704	Central Butte T.	SW 21-21- 4-W3	24	Mun.	481	35	40	1969
713	Shaunavon T.	NE 17- 8-18-W3	22	Mun.	90	—	85	1970
732	Salvador V.	NE 9-37-25-W3	25	Mun.	390	—	8	1967
743	Unity Feeder	NE 29-39-23-W3	25	Ind.	350	—	10	1970
750	Herbert Feeder	NW 36-16-10-W3	24	Ind.	400	—	10	1957
759	DNR	NE 20- 8-26-W3	21	Mun.	48	—	50	1957
765	Landis V.	NW 24-37-18-W3	25	Mun.	528	—	15	1967
773	A. A. Kroeker	SW 19-29- 7-W3	25	Ind.	282	—	8	1970
780	Jubilee Farms	SE 12- 8- 1-W3	22	Ind.	103	—	2	1966
781	Silver Crest Farm	SW 22- 7-29-W2	22	Ind.	100	—	1	1960
807	Lucky Lake V.	SE 25-23- 9-W3	25	Mun.	682	—	15	1964
815	Ace Hog Co.	SE 17-26-14-W3	25	Ind.	—	—	30	1964
821	Rogerson R. B.	NW 27-33-26-W3	25	Ind.	553	—	10	1967
833	Meyers Cattle	SE 17-26-14-W3	25	Ind.	—	—	20	1966
836	RM Grass Lake	NE 28-38-24-W3	25	Ind.	—	—	2	1964
843	Milnice Farm	NW 26-19-20-W3	25	Ind.	340	—	6	1972
855	RM of Estevan	NW 22- 3- 8-W2	22	Mun.	266	—	3	1962
856	RM of Estevan	SE 35- 2- 8-W2	22	Mun.	345	—	3	1962
864	RM of Hearts Hill	NE 20-36- 2-W3	25	Mun.	300	—	6	1962
885	RM of Eagle Creek	NW 28-39-12-W3	25	Mun.	387	—	15	1962
906	Willow Bunch T.	NE 18- 5-27-W2	22	Mun.	129	—	20	1973

*Source	Code	*Source	Code	*Source	Code
Cypress Hills	21	Judith River	25	Blairmore	29
Ravenscrag	22	Ribstone Creek	26	Other Bedrock	30
Eastend	23	Lea Park	27	Undetermined	40
Bearpaw	24	Viking	28		