HYDROGEOLOGIC AND ECONOMIC FACTORS IN DECISION MAKING UNDER UNCERTAINTY FOR NORMATIVE SUBSURFACE DISPOSAL OF FLUID WASTES, NORTHERN WILLISTON BASIN, SASKATCHEWAN, CANADA[1]

Errol G. Dennison[2] and Frank Simpson[3]
Regina, Saskatchewan, Canada

ABSTRACT The normative subsurface waste-disposal condition of no hazard to population, coupled with optimum allocation of drilling funds, can best be 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 current fluid-injection practice. Any decision to drill a disposal well in Saskatchewan is made under considerable uncertainty, which is a reflection of the present reconnaissance level of subsurface information.

Subsurface disposal of fluid wastes in the Williston basin region is at present largely restricted to sandstone and carbonate aquifers (Cambrian through Lower Cretaceous) of the Saskatchewan-Manitoba tectonic shelf. Wastes injected there include (1) oilfield brines, (2) waste brines from exploitation of Devonian potash deposits, (3) waste brines from solution mining of LPG-storage caverns in Devonian halite, (4) refinery sour water and spent caustic, and (5) chlor-alkali plant wastes, partly associated with previously injected herbicide wastes.

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[2]Reservoir Engineer, Saskatchewan Department of Mineral Resources.

[3]Research Geologist, Saskatchewan Department of Mineral Resources.

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Hydrogeologic constraints on development of subsurface waste-disposa systems, not related to reservoir quality of disposal formations but none theless likely to influence waste migration, are (1) proximity of the out crop belt in the north and east, (2) pre-Cretaceous valley systems contrc ling development of fluvial channels up to the present, (3) sinks formed through localized solution of Paleozoic halite, and (4) positive basement features and related overlying structures.

Estimated ultimate capital investments for existing Saskatchewan fluid-injection systems vary from $30,000 to $150,000 in the oil fields to more than $380,000 for some potash-brine disposal wells, and are large ly determined by depth of disposal formation, drilling technique, and wel design. Potash-brine disposal wells in the vicinity of shaft mines inclu the most costly and refined systems, involving directional drilling to formations below the potash unit and mud programs employing fluids compatible with evaporite minerals.

INTRODUCTION

Normative Surbsurface Disposal

Search objectives in petroleum-exploration strategy and disposal-formation evaluation alike are stratigraphic units of good reservoir quality, the former containing commercial accumulations of hydrocarbons and the latter having potential to become repositories of fluid wastes. 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 best be 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; and (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. Although the waste-injection decision system is only a minor part of the total corporate decision system, it will undoubtedly gain in importance 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 Saskatchewan Department of Mineral Resources.

Geologic 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 is presented by Simpson (1973 The outline of the geology relevant to subsurface waste disposal that is given in the present account is based largely on these earlier syntheses.

Strata with waste-disposal potential in southern Saskatchewan and southwestern Manitoba account for 71.9 percent (220,000 sq mi) of the area, but only 38.5 percent (330,000 cu mi) 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 marine (95 percent) sedimentary prism which defines a stable tectonic shelf throughout most of the Canadian part of the Williston basin region, bounded on 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 Figure 2. In general, the strata dip up to 50 ft/mi in a predominantly southwesterly direction. The sedimentary sequence of the northern Williston basin is more than 10,500 ft thick in southeastern Saskatchewan, whereas, in the deepest part of the basin proper of North Dakota, maximum thickness is on the order of 16,700 ft. The succession is characterized by three main lithologic divisions:

1. A lower siliciclastic division (Middle to Upper Cambrian; Ordovician), up to 1,600 ft thick and 12.4 percent of the sedimentary volume;

2. A middle carbonate-evaporite division (Ordovician to Mississippian), up to 4,800 ft thick and 47 percent of the sedimentary volume; and

3. An upper siliciclastic division (Jurassic to Holocene), up to 5,300 ft thick and 40.6 percent of the sedimentary volume.

Formation fluids of great economic importance are the proved 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 reservoirs and Cretaceous nonassociated gas reservoirs. Total dissolved solids and chloride content of formation waters vary because of facies and structure, 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; formation waters of the upper division have higher chloride content in the western belt.

Subsurface disposal of fluid wastes in the Williston basin region as a whole is concentrated to a large extent in the Saskatchewan part of the comparatively shallow, tectonic shelf north of the basin proper. Over 2.599 billion bbl of fluid wastes was injected into subsurface aquifers referable to each of the three gross lithologic divisions in Saskatchewan up to the end of 1972. These were (1) oilfield brines, injected during saltwater disposal (55,960,000 bbl) and pressure maintenance (2,423,980,0(bbl); (2) waste brines (63,440,000 bbl) from exploitation of Devonian potash deposits; (3) waste brines (50,930,000 bbl) from solution mining of LPG-storage caverns in Devonian halite; (4) refinery sour water and spent caustic (3,530,000 bbl); and (5) chlor-alkali plant wastes (221,000 bbl), containing small amounts of mercury, associated with previously injected herbicide wastes (874,000 bbl).

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. Surface occurrences of Phanerozoic strata are confined to scattered exposures of Mesozoic and Paleozoic rocks near the southern perimeter of the Precambrian shield and outcrops of Upper Cretaceous and Cenozoic rocks in broad river valleys and areas of positive relief farther south. Thes‹ rock exposures generally yield little information, and detailed knowledg‹ of the stratigraphy is derived from about 20,000 wells, mostly drilled i‹

exploration for crude oil, natural gas, and potash during the last 25 years. Of great importance to all subsurface search activities of private companies in Saskatchewan are:

1. The series of detailed geologic 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); and

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 oil fields 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 very limited.

2. Petroleum-exploration strategy has been aimed at specific types of resource target, in particular, 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 siliciclastic 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 siliciclastic division is penetrated by all wells, whereas Mississippian, Devonian, and Silurian formations are penetrated by 56.4 percent, 12.4 percent, and 2.5 percent of the wells, respectively. Only 1.5 percent of the wells reached the lower clastic division, and no more than 0.7 percent reached 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 very scarce.

Thus, uncertainty situations characterized by a paucity of hydrogeologic data involve 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.

Scope of Study

The present account is based on part of a comprehensive study of the subsurface waste-disposal potential of the Province of Saskatchewan (Denison and Simpson, in prep.). The objectives here are to outline the hydrogeologic milieu of existing subsurface waste-disposal systems in Saskatchewan and to compare capital costs of these systems, with emphasis on hydrogeologic and economic constraints on widespread attainment of the normative subsurface waste-disposal condition.

The discussions of current subsurface waste-disposal and economic considerations are by both authors. The introduction and hydrogeologic part are by the senior author (F.S.), who coordinated the material and edited the first draft of the paper.

SUBSURFACE WASTE DISPOSAL IN SASKATCHEWAN

General Statement

Fluids injected into subsurface space in Saskatchewan include "natural" waste and nonwaste 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 other fluids are termed "foreign." The "natural" wastes injected into deep aquifers in Saskatchewan are brines, produced during development of oil fields, extraction of potash from sylvite ore, and solution enlargement of caverns in salt for underground gas storage. "Natural" nonwaste fluids injected into subsurface space are oilfield brines, used for pressure maintenance in secondary recovery through waterflooding, 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 currently ranks second among Canadian provinces in petroleum production, during 1971 yielding from 6,685 out of 7,969 well capable of production, 88,458,641 bbl of crude oil, 87,279,562 Mscf of natural gas, and 1,561,884 bbl of LPG, altogether valued at $228,761,584. Total cumulative production of crude oil from 1940 to the end of 1971 was 1.131 billion bbl, and the gross value of sales reached a total of $2,506,360,316. Total cumulative production of natural gas to the end of 1971 was 546.77 billion cu ft. Production is obtained from reservoirs ranging in age from Ordovician to Late Cretaceous. Total original recoverable reserves of crude oil in Saskatchewan to the end of 1971 were estimated to be 2.020 billion bbl. Medium- and high-gravity crude oils in the Mississippian reservoirs of southeastern Saskatchewan accounted for 61.6 percent of these reserves.

The distribution of oil and gas production in the study area and Saskatchewan government-designated disposition areas I through IV are presented in Figure 3. Table 1 shows total cumulative volumes of brines injected into the upper siliciclastic 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, and 1,610 are classified as pressure-maintenance wells, in which brine produced with the oil is used to displace crude oil and thus enhance recovery. Depths of injection formations range from 1,750 ft in area I to 6,500 ft in area IV. Injection rates are low to moderate (1 to 200 U.S. gpm), 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 percent of all oilfield brines injected into deep aquifers in Saskatchewan.

Potash-Brine Disposal

Soluble potassium minerals are mined from the Prairie Evaporite (Middle Devonian) at ten main localities in Saskatchewan. Conventional shaft mining operations are employed at nine plants (Fig. 4) where soluble potassium minerals occur in beds at depths of no more than 3,500 ft. Below this depth, mine faces are likely to be unstable and solution mining is favored. Solution extraction has been pioneered in Saskatchewan by Kalium Chemicals Ltd., at Belle Plaine, west of Regina, where the potassium mineral unit mined is encountered at a depth of nearly 5,000 ft. 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. Total recoverable reserves of commercial potassium minerals are estimated at 118 billion short tons of KCl, 110 billion tons of which may be recovered by solution mining (Holter, 1969). It should be noted that the potash shaft mines themselves represent about 2 billion cu ft of potential subsurface storage space.

Potash-brine disposal systems of Saskatchewan are listed in Table 2. Eight of these systems are currently in operation; five of the systems listed are pilot disposal projects now suspended or abandoned. Current systems are characterized by high injection rates (175 to 1,100 U.S. gpm) and moderate to high injection pressures (130 to 910 psig). Such systems involve injection of large volumes of brine for the duration of the life of a mine (1-2 decades), with disposal discontinued only for short periods of maintenance during that time. In the vicinity of shaft mines, disposal is made into aquifers of the basal siliciclastic division and that part of the carbonate-evaporite division below the Prairie Evaporite, to minimize the danger of flooding within the mine workings. Multi-zone 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.

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 liquefied petroleum gases. There are seven salt-cavern storage facilities in Saskatchewa with a total of 18 caverns (Fig. 5; Table 3), giving an aggregate cavern storage capacity of 8,250,000 bbl. The subsurface waste-disposal systems associated with these cavern-storage facilities are listed in Table 4. Of the ten wells listed, only five are presently in operation, with moderate injection rates (150-300 U.S. gpm) and frequently high injection pressures of up to 1,750 psig. The life of a salt-cavern brine-disposal well is determined by growth of the cavern with which it is associated; that is, injection may continue for a period of a year or more. Disposal has been made into formations at moderate depths (1,712-3,571 ft), referable to the carbonate-evaporite division and lowermost part of the upper siliciclastic division.

Refinery and Chemical-Plant Waste Disposal

Disposal of refinery wastes into the subsurface is effected by two operators in the Regina district (Table 5). Consumers' Co-operative

Refineries Limited injects spent caustic containing phenols and sulfides into the lower part of the upper siliciclastic group at low injection rate (3 U.S. gpm) and low pressure (gravity). Up to September 1972, the waste contained about 70 percent receiver water, and spent caustic made up the remainder. Imperial Oil Enterprises, Ltd., disposes of sour water (680-740 bbl/day) and spent caustic (15-30 bbl/day) into limestones near the top of the carbonate-evaporite group; the volumes depend on the rate of crude production. Injection rates are low (22 U.S. gpm) and pressure moderate (350 psig). Table 5 includes data on disposal of refinery wastes by Imperial Oil Enterprises, Ltd., at Virden, Manitoba, and by Husky Oil Operations Ltd. at Lloydminster.

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 siliciclastic division near Saskatoon from 1963 until the herbicide plant was shut down in 1970. The wastes were neutralized phenolic brines with traces of 2,4-D, 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 (1-50 ppm; average value 5 ppm) generated by a chlor-alkali plant. Injection rates have been low (20 U.S. gpm) and injection pressures moderate (150-400 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.

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.

Perspectives on Subsurface Disposal in Saskatchewan

The distribution of subsurface fluid-injection systems in Saskatchewan is shown in Figure 6, and 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 6 and 7. The upper siliciclastic division receives about 42 percent of all injected fluids, whereas the carbonate-evaporite and basal siliciclastic divisions receive on the order of 57.15 percent and 0.85 percent, respectively.

However, if oilfield injection systems are not taken into consideration, the upper clastic division is seen to receive 25.62 percent of the fluid wastes (30,485,000 bbl), the carbonate-evaporite division 55.87 percent (66,480,000 bbl), and the basal clastic division 18.51 percent (22,030,00 bbl). The percentage given for the carbonate-evaporite division is no doubt too high and that for the basal siliciclastic division too low by a corresponding amount, because of uncertainties relating to multi-zone injection in four wells.

As is shown in Table 7, 96.11 percent by volume of injected fluids, not associated with oilfield systems, is "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, 196 Vonhof and van Everdingen, 1972) and Alberta (Vonhof and van Everdingen, 1972), 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.

HYDROGEOLOGIC MILIEU OF SUBSURFACE WASTE DISPOSAL

General Statement

The commercial accumulations of economically important formation fluids, which are the oil and gas pools of Saskatchewan, reflect dominance of the stratigraphic trap (Christopher et al., 1971; 1973). Comparable reservoir geometries without the presence of hydrocarbons could provide adequate subsurface space for disposal of fluid wastes (Fig. 7). Thus, essentially similar rationales characterize the search phases of both petroleum-exploration and fluid-injection decision systems. Althou 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 changes and structural features. The former reflect differences in depositional environment, and the latter evidence 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 peculiarities of the cratonic setting and their possible implications for migration of fluids injected under high pressure is of vital importance in subsurface waste-disposal operations 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 11-20 ft/mi, with the strike changing from northwesterly to northerly across Saskatchewan into Manitoba;
2. Steepening of the dip to as much as 50 ft/mi 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 4th Meridian and lat. 52° (Fig. 8);
4. The prominent lineaments which are the Meadow Lake escarpment of west-central Saskatchewan and the Nelson River feature of eastern Saskatchewan and Manitoba (Fig. 8); and
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 depostion of the Phanerozoic sequence led to folding of the sedimentary units, 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.

Basal Siliciclastic Division

The basal siliciclastic sequence (Fig. 9) consists of sandstones and shales of 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 lie on the Precambrian basement. These strata are exposed in east-central Saskatchewan and central Manitoba where 10 to almost 100 ft of the Winnipeg Formation constitutes the entire basal siliciclastic sequence.

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

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

Waste brines from potash-mining operations are injected into aquifers of the basal siliciclastic division in four systems in southeast Saskatchewan (multi-zone injection into Interlake carbonate rocks and Winnipeg sandstones) and in three systems in the Saskatoon district (Deadwood Formation). The main restriction on disposal is the increase in proportion of reservoir heterogeneities as a result of argillaceous intercalations and the corresponding loss of reservoir quality westward in the Deadwood Formation and southeastward in the Winnipeg Formation.

Carbonate-Evaporite Division

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

The formations older than the Prairie Evaporite are characterized by southeastern and western areas of high salinity (94,900-189,800 mg/l chloride), separated in both areas 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 strata and directly underlying strata (Hitchon, 1964). The corridor coincides with a northeast-trending positive feature of the lower Paleozoic surface and also with the "salt-free" area of central-south and southwest 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 exhibit high chloride content of formation waters in southeastern Saskatchewan (greater than 132,860 mg/l and 94,900 mg/l, respectively); values of less than 18,980 g/l are characteristic throughout the rest of southern Saskatchewan (Hitchon, 1964), suggesting general updip flow of brines from the Williston basin proper.

The carbonate-evaporite division receives waste and nonwaste fluids representing all the major fluid categories injected into the Saskatchewan subsurface (Fig. 10). Injection of oilfield brines is largely restricted to the Mississippian oil-producing units of the southeast. Of the potash-brine disposal systems, four are associated with shaft mines and involve injection well below the Prairie Evaporite into the Silurian Interlake Group, whereas one in the vicinity of a solution-mining operation involves injection into Mississippian Souris Valley carbonate rocks. One abandoned potash-brine disposal well injected into the Upper Devonian Birdbear Formation. The Souris Valley Formation is the disposal unit in four salt-cavern brine-disposal systems and one refinery-waste disposal system. The Duperow Formation receives "natural" brines from one 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.

Upper Siliciclastic Division

Jurassic, Cretaceous, Tertiary, and Pleistocene siliciclastic units form the third division (Fig. 11), which unconformably overlies the carbonate-evaporite sequence in southern Saskatchewan and southwestern Manitoba and onlaps the Precambrian basement in central Saskatchewan. Terrestrial Triassic-Jurassic argillaceous red sandstones, succeeded by marine redbeds of anhydrite and dolomite and white dolomitic limestones, form the basal deposits. These are overlain by Middle Jurassic gray marine shales, sandstones, and carbonate rocks, which are succeeded vertically by Upper Jurassic marine shales and sandstones. Lacustrine-fluvial, fluviomarine, and marine sandstones and shales of the Mannville Group (basal Cretaceous) lie unconformably on Jurassic, Mississippian, and Devonian strata northward. These continental-to-marine 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 Formation of the Montana Group. Continental environments of 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 are generally low (less than 18,980 mg/l chloride) in Jurassic units, the Mannville Group, and the Viking Formation. The Cretaceous rocks, however, contain brines with a relativel 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 sandstone bodies, with respect to the elevation of the present ground surface, and by the resulting artesian flow from sandstone aquifers, particularly from those belonging to the Mannville Group in south-central Saskatchewan.

Oilfield-brine injection is directed into the Jurassic Shaunavon and Roseray Formations and Cretaceous Mannville sequence of the southwest and the Mannville and Viking of two districts in west-central Saskatchewan. All other injection of fluids is into the Mannville Group: five salt-caver brine-disposal systems, one refinery-waste disposal system, and one chemical-plant disposal system. Four pilot potash-brine disposal systems (thre abandoned, one 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 has a northeasterly increase in sandstone content on the structural terrace north of the North Saskatchewa River (Simpson, in press), thus providing hydraulic continuity between the Mannville Group and preglacial and glacial aquifers at the bedrock surface

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. 12). The largest of these is a roughly triangular, salt-free depression in southwest and central-south Saskatchewan, approximately 23,000 sq mi 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 and regional salt-solution structures are narrow, elongate troughs and smaller-scale, subcircular, commonly fracture bounded depressions. On the basis of thickness 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 Cretaceou or early Tertiary time; the earliest solution events were restricted to local channels, which subsequently coalesced to give the present edge of the Prairie Evaporite.

The relation between positive relief 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 the development of fluvial channel networks incised into the Devonian, Mississippia and Jurassic rocks, which appear in order of decreasing age southward at the pre-Cretaceous unconformity; such solution depressions also influenced the arrangement of succeeding fluvial and fluviomarine channel sandstones of the Mannville Group (Christopher, in prep.). Mannville paleotopographi features are mimicked by overlying structures in the younger, marine Cretaceous deposits; they correspond closely to preglacial 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 relations 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--all render the Mannville succession largely unsuitable for injection of fluid wastes based on the present reconnaissance type of subsurface information.

Fluid Flow in Northern Williston Basin Region

Consideration of the mathematical models of groundwater movement based on hydraulic continuity of the groundwater regime, as developed by Tóth (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, b) 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 siliciclastic division, the Upper Devonian and Mississippian carbonate rocks, and the Mannville sandstone aquifers, tend to control the overall flow pattern, which is developed in a northeasterly direction. As noted by Christopher (1961), the central Montana uplift is the recharge area for meteoric waters flushing the Paleozoic strata of southern Saskatchewan. Figure 13 shows the distribution of Paleozoic 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 ft, and Hitchon (1969a) 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 contribut 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. 14). 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.

An extensive blanket of glacial drift, locally exceeding 900 ft in thickness, covers much of southern Saskatchewan. Within these deposits, several distinct till units, separated by stratified drift, can 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 predominantly fluvial origin also occur as preglacial and early synglacial valley fill on the bedrock surface of southern Saskatchewan (Whitaker and Christiansen, 1972), and they constitute important aquifers.

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 Figure 15. Types of disposal-well completion favored in Saskatchewan are illustrated in Figure 16, and the number of disposal systems corresponding to each completion type is listed by waste category, exclusive of oilfield-brine injection wells, in Table 8.

In Table 9, an attempt is made to summarize for the first time costs for Saskatchewan fluid-injection systems currently in use, on the basis of data supplied by operators. Shortcomings of Table 9 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.

2. Potash-brine disposal wells, more complex in design and commonly 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, surface disposal would cost on the order of 2-3 times the estimated ultimate capital investment for a subsurface disposal system.

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 a 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 the related uncertainties, as well as considerations of well design, which must take into account high injection rates and pressures during a well life of 1-2 decades. Hole size may range from 17 1/2 in. in diameter over the first 500 ft to 8 3/4 in. down to total depth, and costs of casing (lined) and tubing strings and of 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 and 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 well, 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 low drilling costs, by comparison with potash-mining systems. Hole sizes usually range from 15 in. in diameter to 8 3/4 in. 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 consider reflects both the low level of existing information on the geologic setti 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.

Cost Estimates of Subsurface and Surface Disposal Systems

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 2-3 time more costly than subsurface waste disposal and would also result in loss of wide areas of farmland over periods of many years. Lagoons and natura depressions currently in use by operators are in most cases located near major, undeveloped, freshwater aquifer systems in glacial deposits (Vonhof, in press), and this potential hazard to future water resources would be greatly increased in the absence of subsurface disposal faciliti The writers consider the cost-estimate range given in Table 9 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. Th 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.

CONCLUDING REMARKS

1. Subsurface disposal of waste fluids into confined aquifers in Saskatchewan is a high-risk venture which involves multiple conflicting objectives, immediate costs and benefits accruing to various interest groups, and consequences for environmental management possibly extending far into the future--all based on decision under uncertainty, arising from the reconnaissance nature of subsurface information throughout most of the province. Only in the oilfield districts of southeastern and western Saskatchewan is detailed subsurface information available for use by operators drilling brine-injection wells as disposal and pressure-maintenance facilities.

2. Waste fluids with constituents commonly found in the subsurface constitute the dominant category of waste injected into the Saskatchewan subsurface. These are brines produced during development of oil fields, extraction of potash from sylvite ore, and solution enlargement of caverns in salt for underground gas storage. Potash-brine disposal is characterized by high injection rates and pressures and by long well life of 1-2 decades. Salt-cavern brine disposal is carried out at moderate to high injection rates and pressures and over periods of only a few years for a given system. Subordinate amounts of toxic wastes with constituents foreign to the subsurface environment, generated by two refineries at Regina and by a herbicide and chlor-alkali plant at Saskatoon, are also injected into deep aquifers at low rates and pressures.

3. Excellent Cambrian and Ordovician sandstone aquifers and Silurian carbonate aquifers currently receiving potash waste brines at depths in the range of 3,670 to 4,692 ft are the deepest disposal units and, though poorly known, 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 brines and refinery wastes. However, collapse structures and associated fractures

in these strata, above the sites of solution removal of Middle Devonian evaporite beds, may facilitate vertical migration of waste fluids to higher aquifers and should be taken into account during the search phase of decision making. Fluvial and fluviomarine sandstone bodies of Early Cretaceous age constitute the shallowest disposal aquifers at present; wastes of all main categories are injected at depths in the range of 1,600 to 2,690 ft. These 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 of fluvial origin, and present-day drainage patterns, controlled to a large extent by salt-solution phenomena.

4. At present, subsurface disposal of fluid wastes is the only viable alternative to surface storage of brines in lagoons and natural depressions, which would occupy many acres of potential farmland and would present the possible threat of contamination of groundwater in drift aquifers. Estimates of ultimate capital investment for surface disposal systems are generally at least 2-3 times the estimated ultimate cost of the corresponding subsurface waste-disposal system.

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TABLE 1. Subsurface Fluid-Injection Systems in Saskatchewan: Oilfield-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 (bbls) [1]
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

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

TABLE 2. 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.

TABLE 3. 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	1,400,000

TABLE 4. **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.

TABLE 5. Subsurface Fluid-Injection Systems in 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 6. 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.

TABLE 7. Subsurface Fluid-Injection Systems in Saskatchewan: Volumes of Injected Fluids 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
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 8. 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] Bracketed values relate to multizone completions.

TABLE 9. Capital Expenditure in Dollars[1] for Different Types of Subsurface Waste-Disposal Systems 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) (drilling, completion and casing combined)	0 - 58,000 43,000 (2)
COMPLETION	1,000 - 8,000	57,000 - 137,000 89,000 (7) (completion and casing combined)		-
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 5,800 (4)	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.

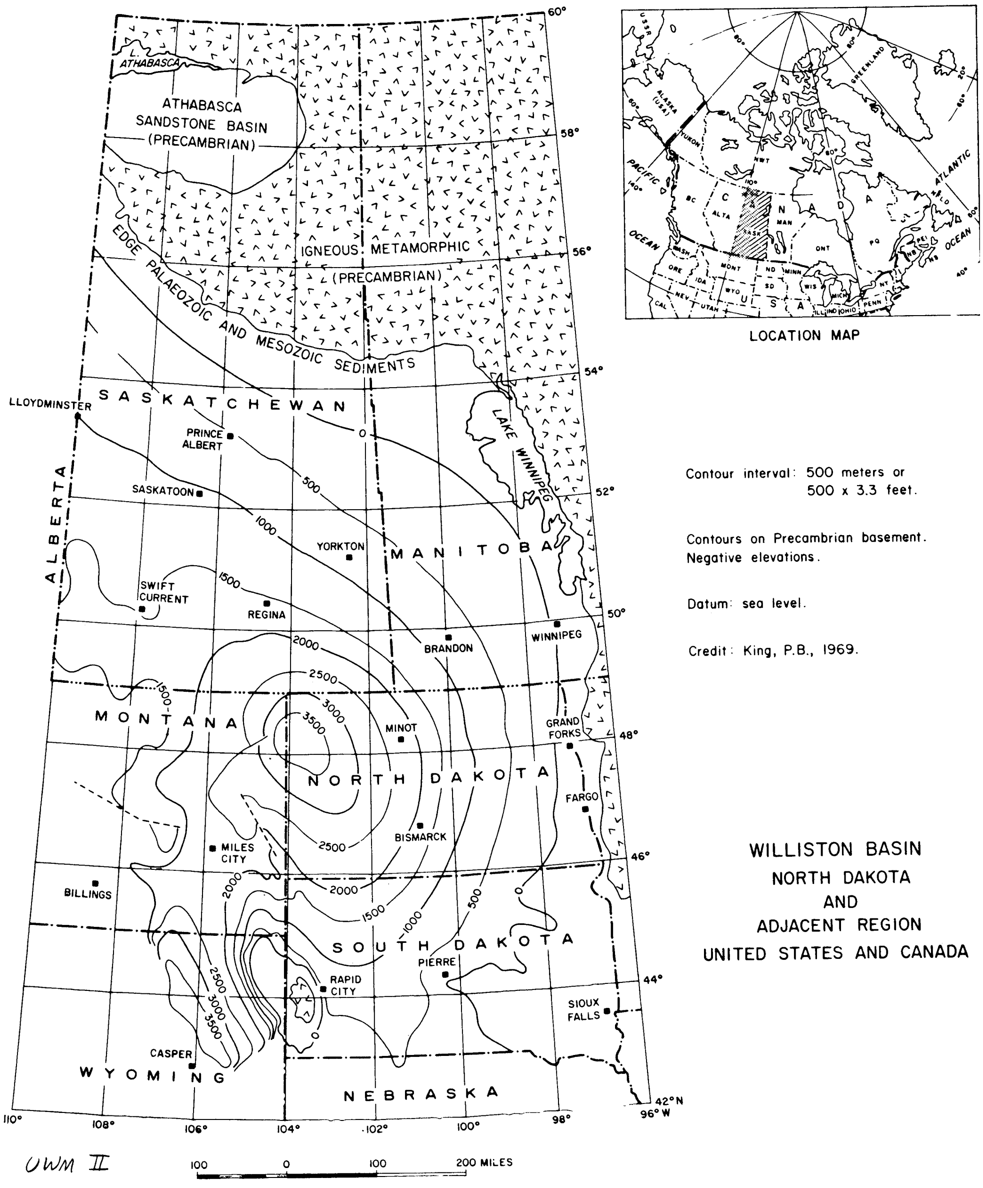
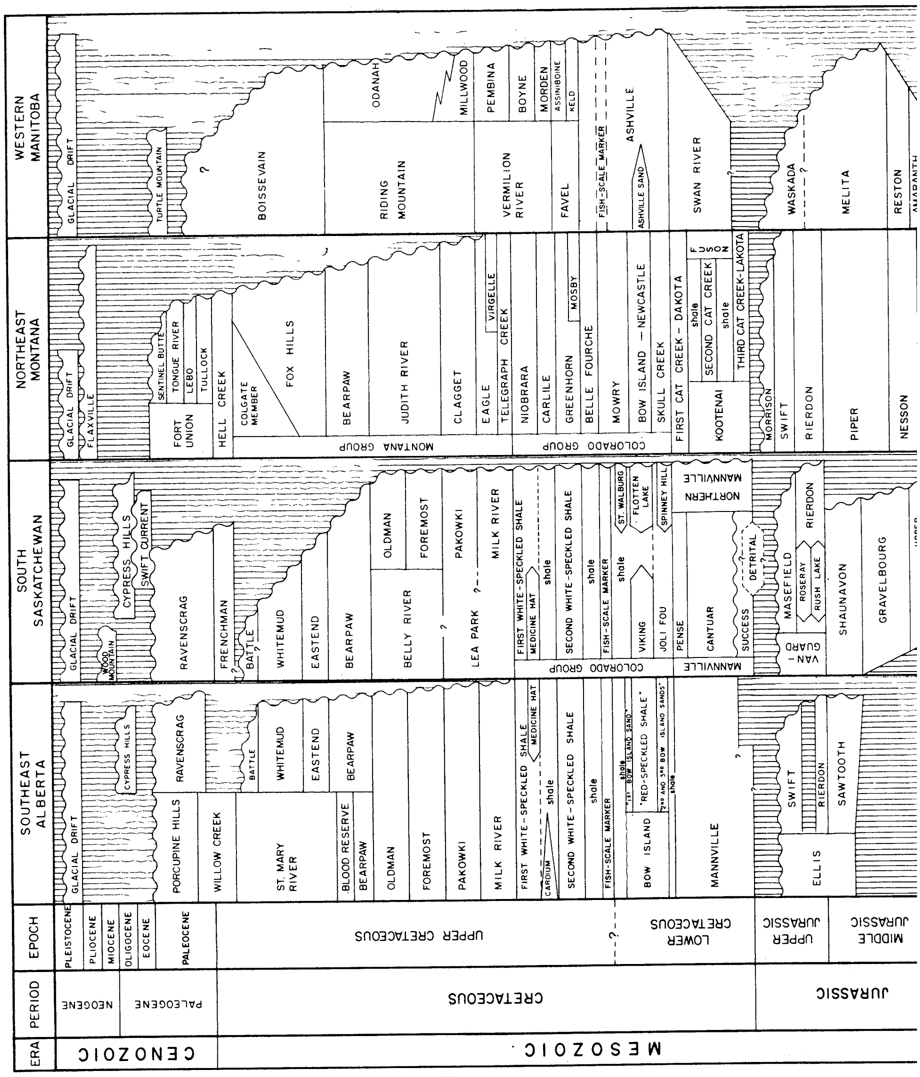

LOCATION MAP
Contour interval: 500 meters or
500 x 3.3 feet.
Contours on Precambrian basement.
Negative elevations.
Datum: sea level.
Credit: King, P.B., 1969.
WILLISTON BASIN
NORTH DAKOTA
AND
ADJACENT REGION
UNITED STATES AND CANADA
ATHABASCA SANDSTONE BASIN (PRECAMBRIAN)
IGNEOUS METAMORPHIC (PRECAMBRIAN)
EDGE PALAEOZOIC AND MESOZOIC SEDIMENTS
SASKATCHEWAN
MANITOBA
ALBERTA
MONTANA
NORTH DAKOTA
SOUTH DAKOTA
WYOMING
NEBRASKA
LAKE WINNIPEG
100 0 100 200 MILES
UWM II

FIG. 1.


ERA
PERIOD
EPOCH
SOUTHEAST ALBERTA
SOUTH SASKATCHEWAN
NORTHEAST MONTANA
WESTERN MANITOBA
CENOZOIC
MESOZOIC
NEOGENE
PALEOGENE
CRETACEOUS
JURASSIC
PLEISTOCENE
PLIOCENE
MIOCENE
OLIGOCENE
EOCENE
PALEOCENE
UPPER CRETACEOUS
LOWER CRETACEOUS
UPPER JURASSIC
MIDDLE JURASSIC
GLACIAL DRIFT
CYPRESS HILLS
PORCUPINE HILLS
RAVENSCRAG
WILLOW CREEK
ST. MARY RIVER
BATTLE
WHITEMUD
EASTEND
BEARPAW
BLOOD RESERVE
OLDMAN
FOREMOST
PAKOWKI
MILK RIVER
FIRST WHITE-SPECKLED SHALE
MEDICINE HAT
CARDIUM
shale
SECOND WHITE-SPECKLED SHALE
FISH-SCALE MARKER
BOW ISLAND
"RED-SPECKLED SHALE"
MANNVILLE
SWIFT
RIERDON
SAWTOOTH
ELLIS
WOOD MOUNTAIN
SWIFT CURRENT
FRENCHMAN
BELLY RIVER
LEA PARK
VIKING
JOLI FOU
PENSE
CANTUAR
SUCCESS
DETRITAL
ST. WALBURG
FLOTTEN LAKE
SPINNEY HILL
NORTHERN MANNVILLE
COLORADO GROUP
MANNVILLE
VANGUARD
MASEFIELD
ROSERAY
RUSH LAKE
SHAUNAVON
GRAVELBOURG
FLAXVILLE
FORT UNION
SENTINEL BUTTE
TONGUE RIVER
LEBO
TULLOCK
HELL CREEK
COLGATE MEMBER
FOX HILLS
JUDITH RIVER
CLAGGET
EAGLE
VIRGELLE
TELEGRAPH CREEK
NIOBRARA
CARLILE
GREENHORN
MOSBY
BELLE FOURCHE
MOWRY
BOW ISLAND — NEWCASTLE
SKULL CREEK
FIRST CAT CREEK - DAKOTA
KOOTENAI
SECOND CAT CREEK
THIRD CAT CREEK-LAKOTA
MORRISON
PIPER
NESSON
MONTANA GROUP
TURTLE MOUNTAIN
BOISSEVAIN
RIDING MOUNTAIN
ODANAH
MILLWOOD
PEMBINA
VERMILION RIVER
BOYNE
MORDEN
ASSINIBOINE
KELD
FAVEL
FISH-SCALE MARKER
ASHVILLE
ASHVILLE SAND
SWAN RIVER
WASKADA
MELITA
RESTON

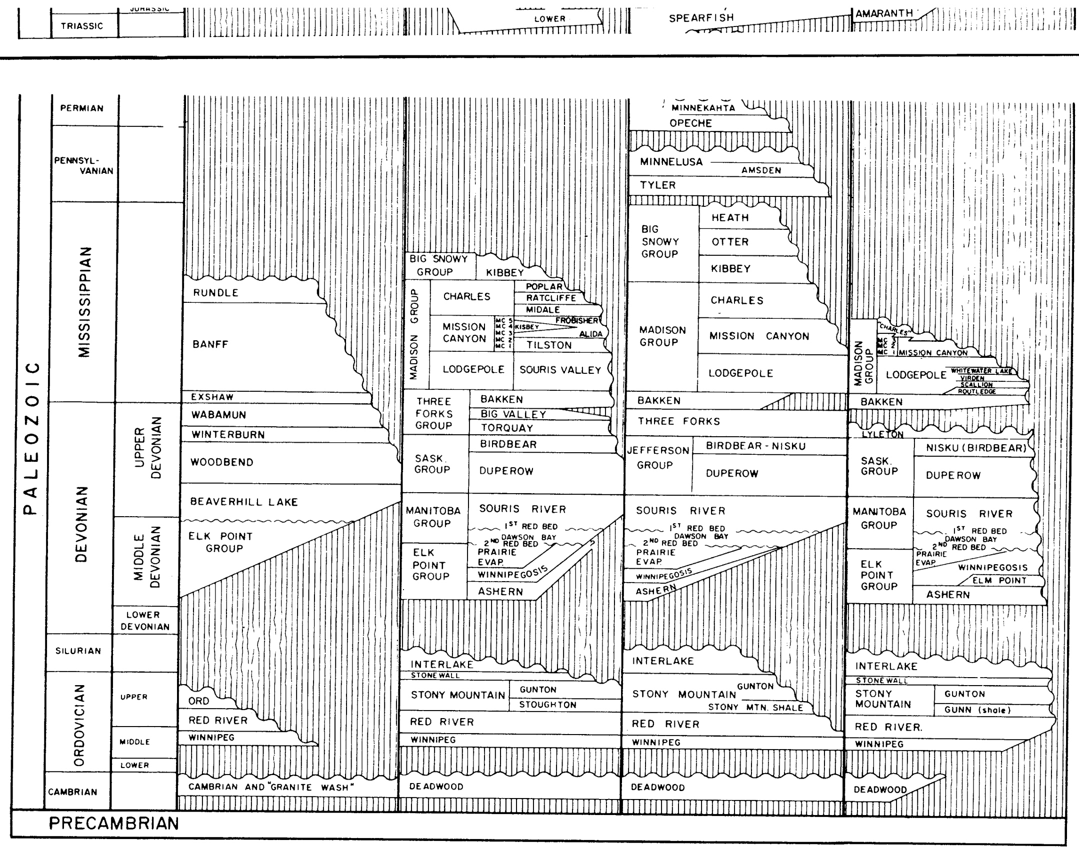


FIG. 2--Stratigraphic correlation chart for northern Williston basin region.

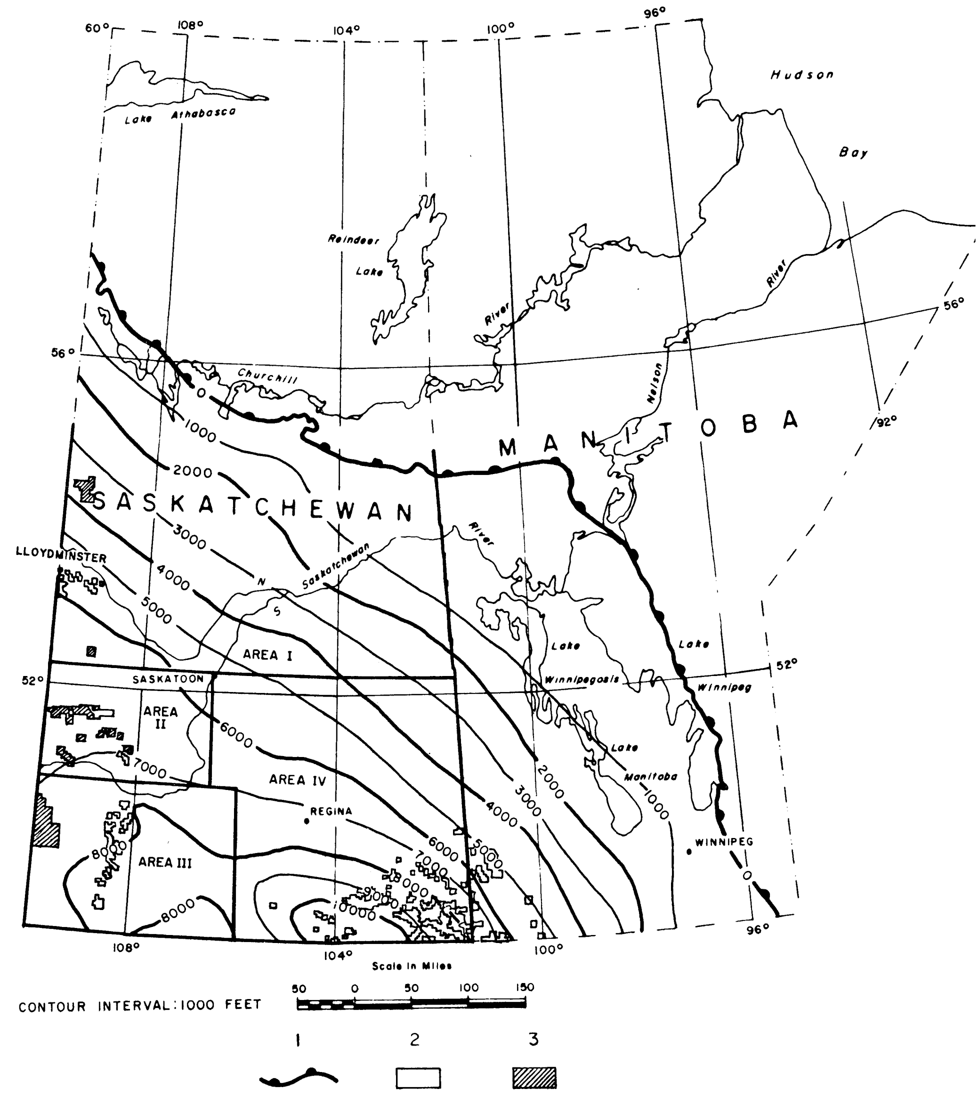


FIG. 3--Distribution of crude oil and natural gas production on isopach map of Phanerozoic sequence, Saskatchewan and Manitoba. 1, southern perimeter o: Precambrian shield; 2, oil production; 3, natural gas production.

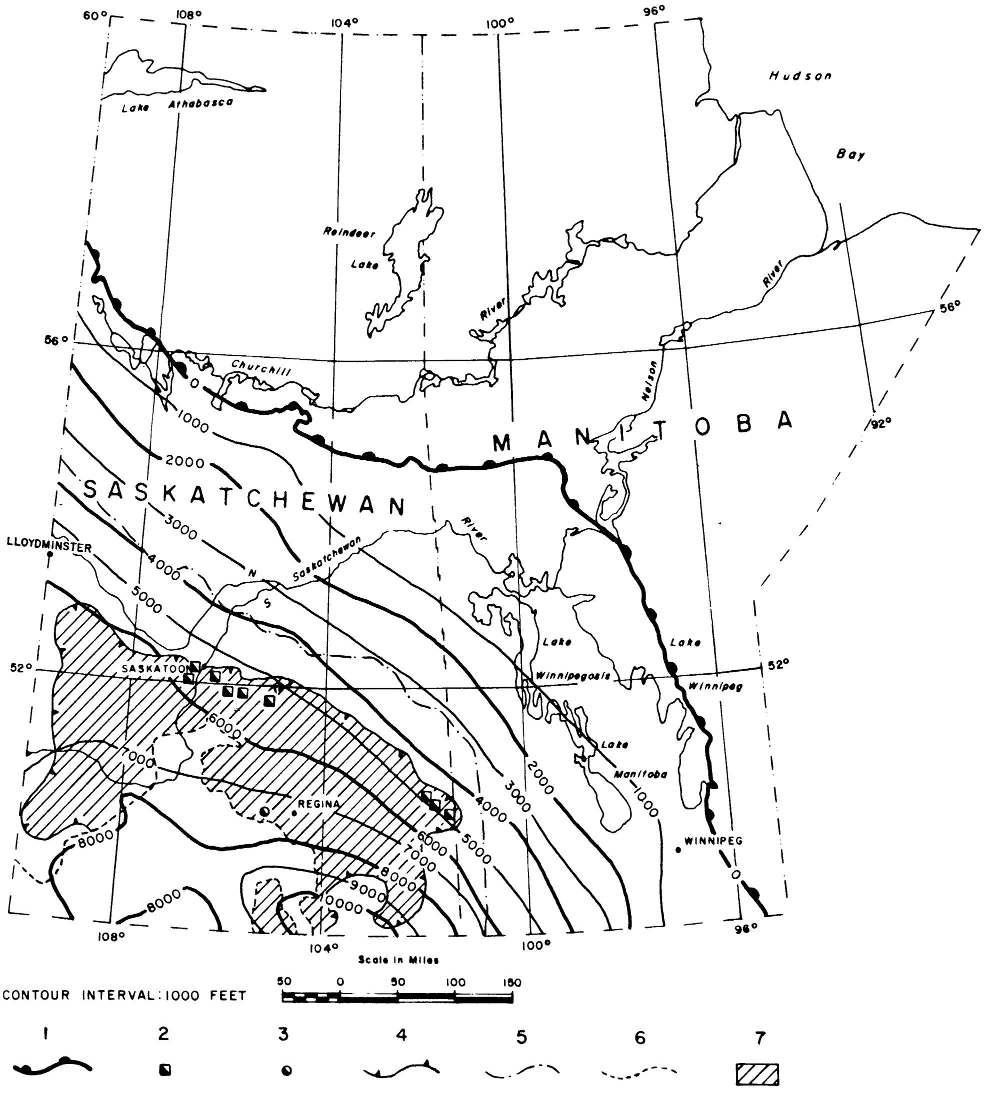


FIG. 4--Distribution of potash production from Prairie Evaporite (Middle Devonian) on isopach map of Phanerozoic sequence, Saskatchewan and Manitoba. 1, southern perimeter of Precambrian shield; 2, shaft mining; 3, solution mining; 4, limit of soluble potassium minerals; 5, limit of salt; 6, area where Prairie Evaporite absent; 7, area of potash production potential.

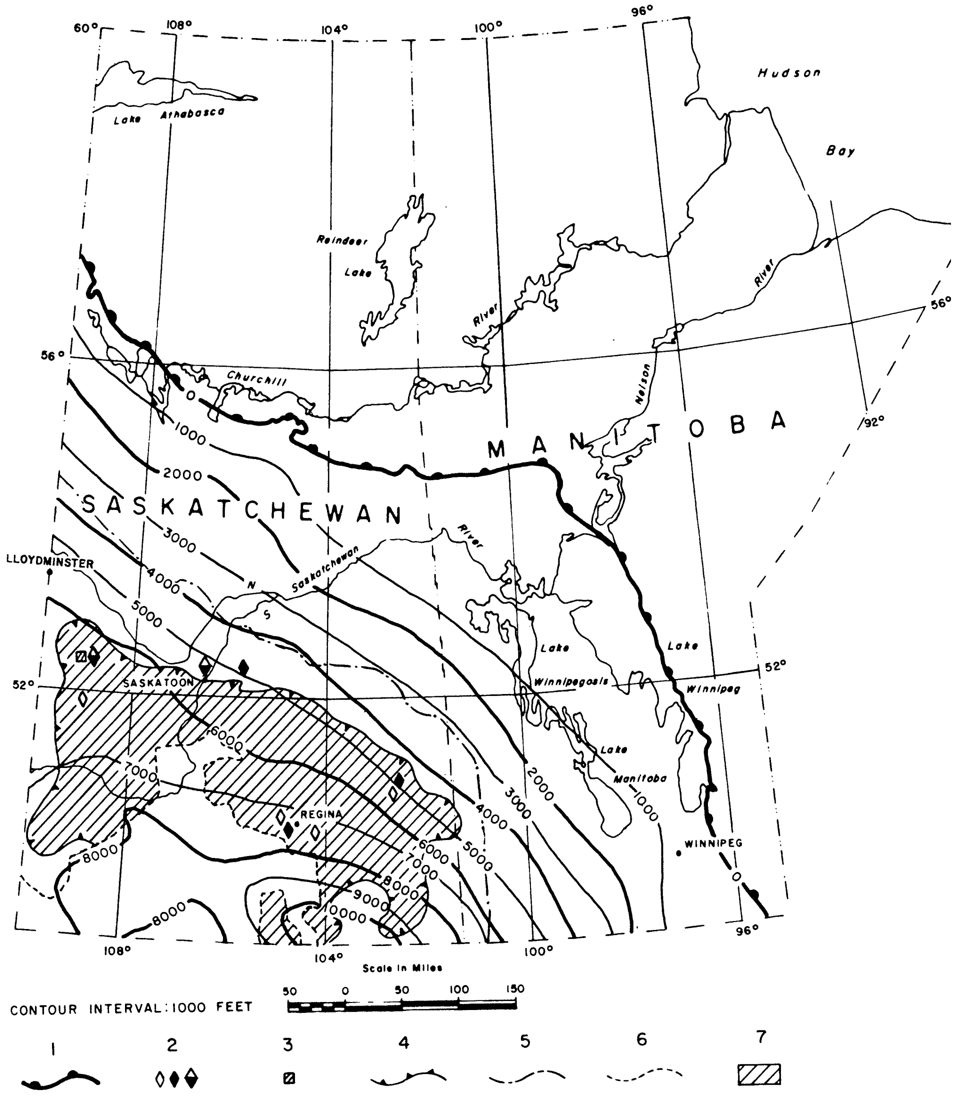


FIG. 5--Distribution of caverns in halite of Prairie Evaporite (Middle Devonian) on isopach map of Phanerozoic sequence, Saskatchewan and Manitoba 1, southern perimeter of Precambrian shield; 2, LPG storage cavern, natural gas storage cavern, and chemical-plant facility; 3, aquifer natural gas storage; 4, limit of soluble potassium minerals; 5, limit of salt; 6, area where Prairie Evaporite absent; 7, area of potash production potential.

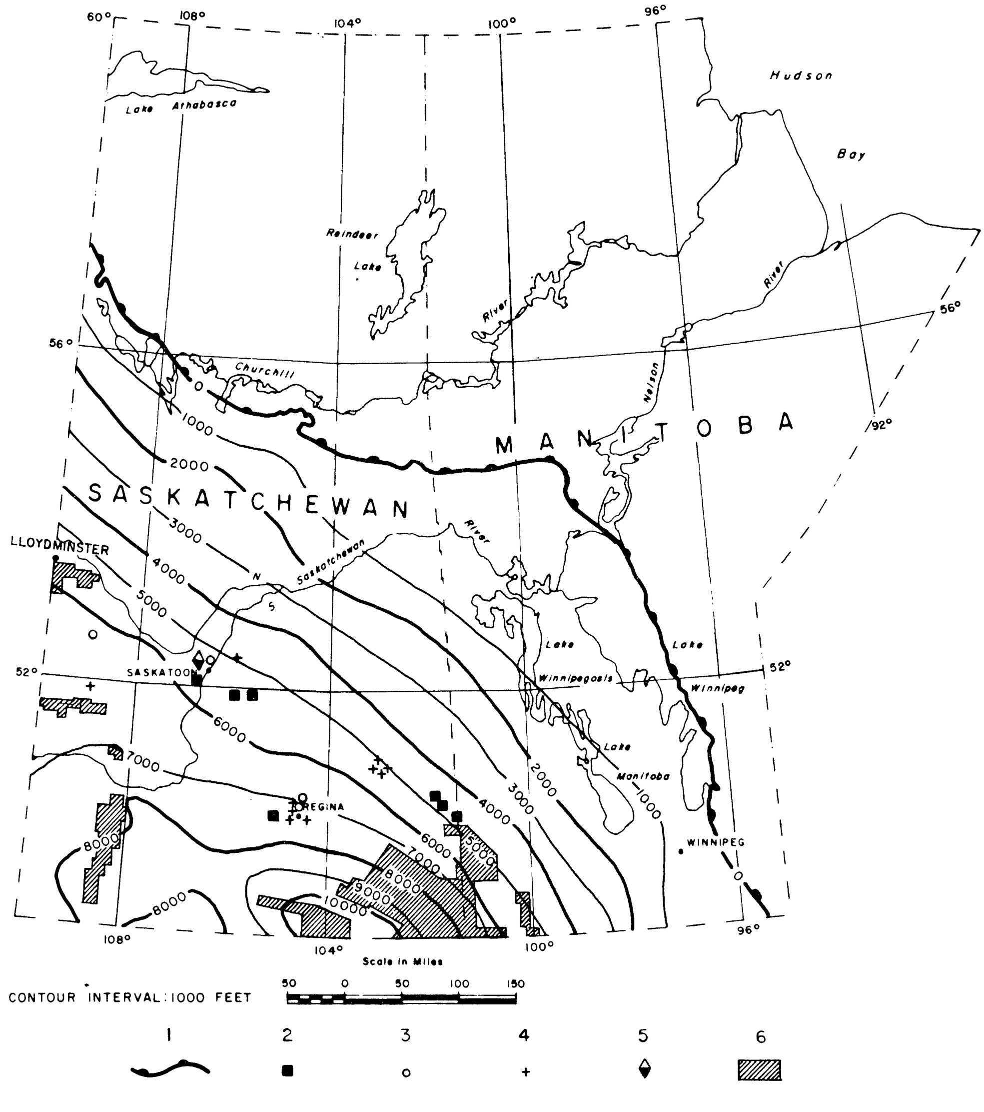
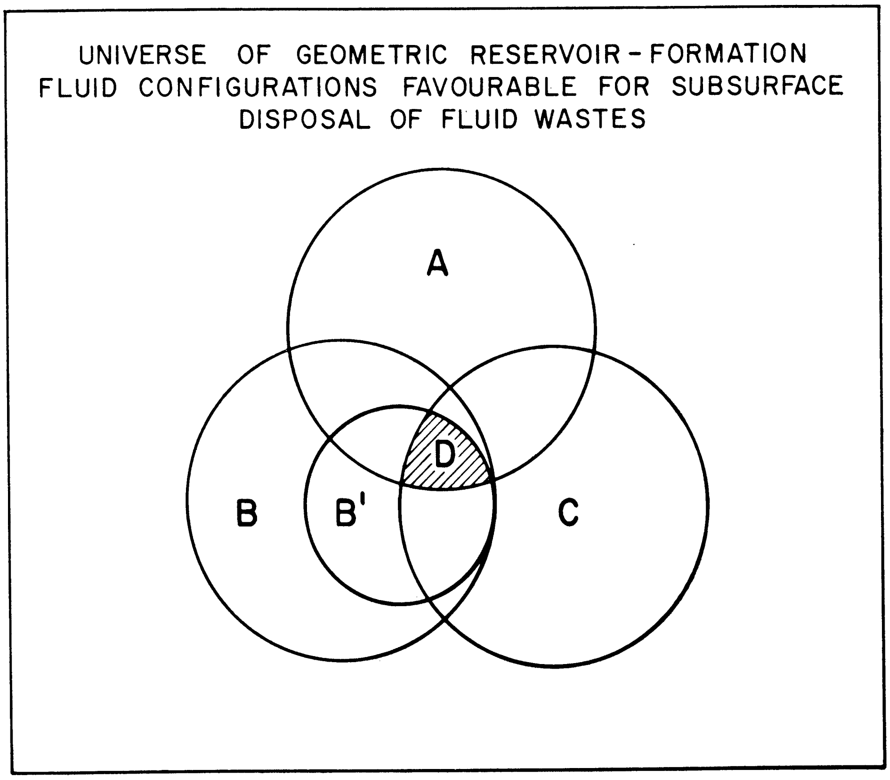


FIG. 6--Distribution of subsurface waste-disposal systems on isopach map of Phanerozoic sequence, Saskatchewan and Manitoba. 1, southern perimeter of Precambrian shield; 2, potash-brine injection; 3, refinery and chemical-plant waste injection; 4, salt-cavern brine injection; 5, chemical-plant waste disposal in salt caverns; 6, oilfield-brine injection.



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

FIG. 7--Venn diagram to show geometric reservoir - formation-fluid configurations favorable for subsurface waste disposal, and disposal-aquifer condition.

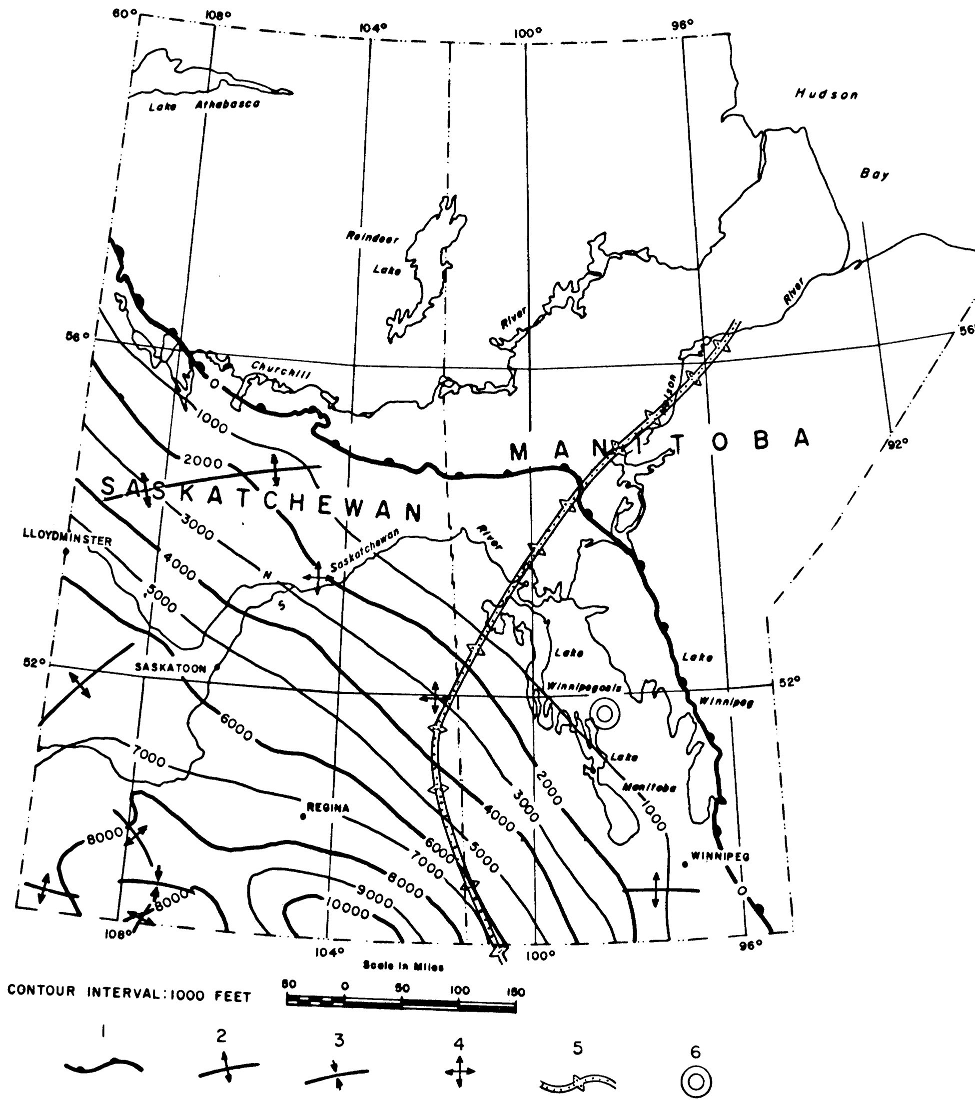


FIG. 8--Structural features of Precambrian basement with isopachs of Phanerozoic sequence superimposed, Saskatchewan and Manitoba. 1, southern perimeter of Precambrian shield; 2, positive feature; 3, negative feature; 4, local positive gravity anomaly; 5, Nelson River gravity high; 6, Lake St. Martin structure.

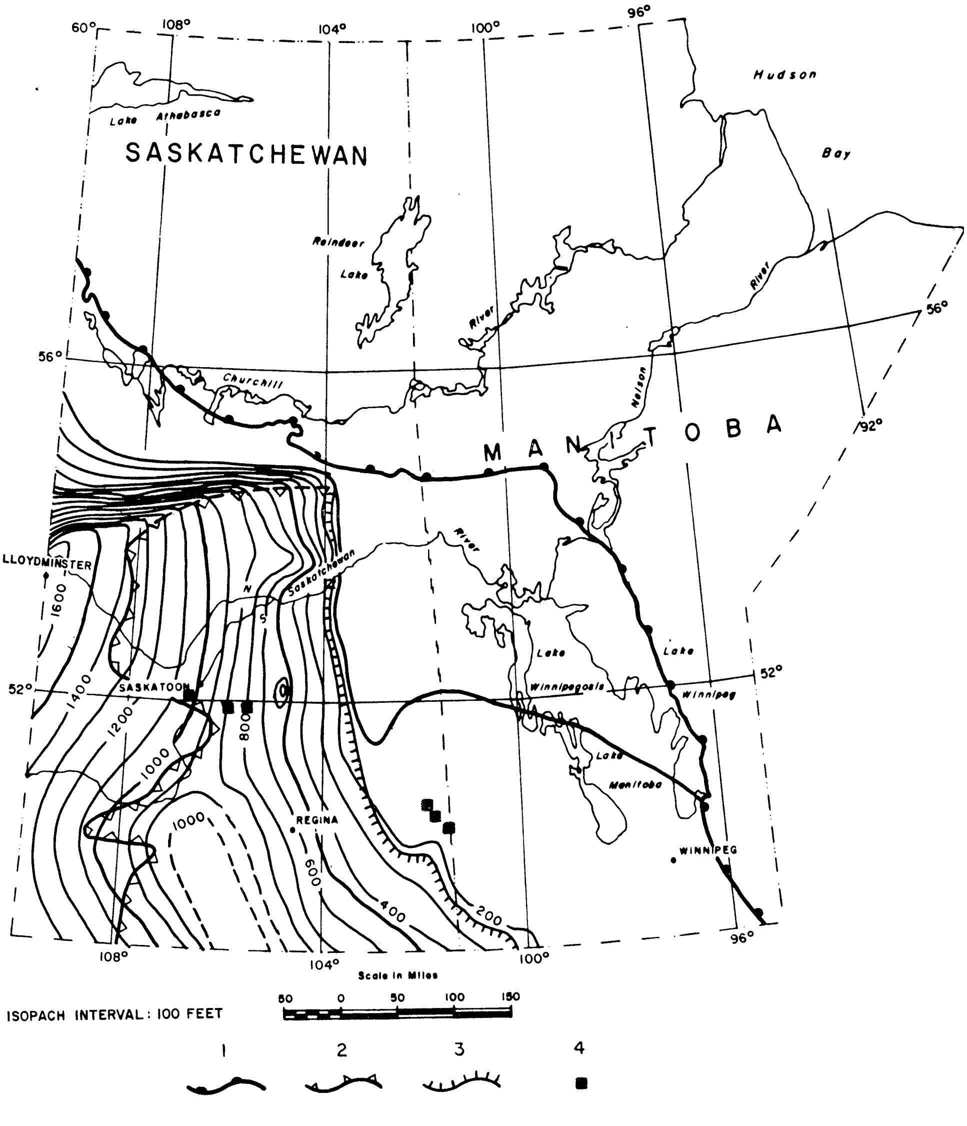


FIG. 9--Basal siliciclastic division in Saskatchewan and Manitoba: isopachs and distribution of subsurface waste-disposal systems. 1, southern perimete of Precambrian shield; 2, limit of Winnipeg Formation; 3, limit of Deadwood Formation; 4, potash-brine injection.

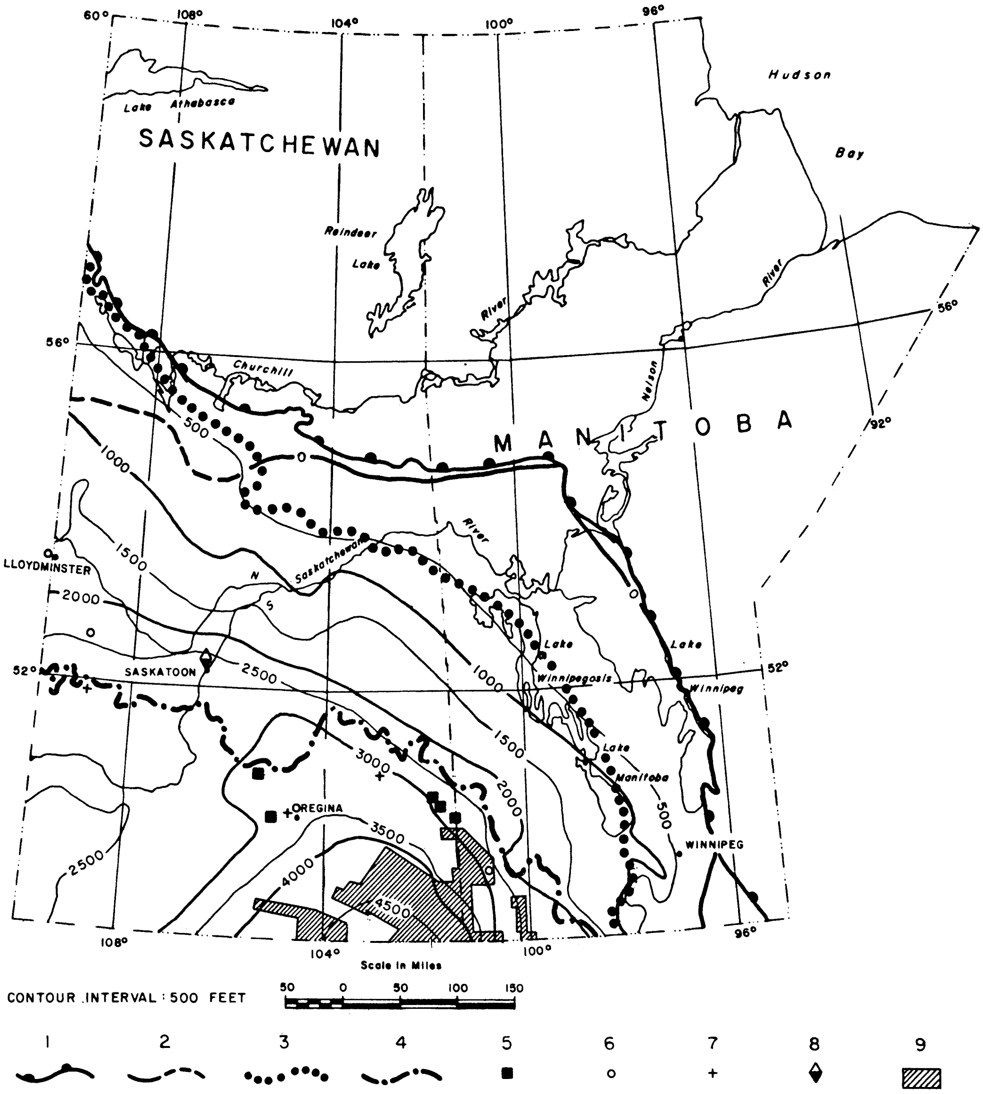


FIG. 10--Carbonate-evaporite division in Saskatchewan and Manitoba: isopachs and distribution of subsurface waste-disposal systems. 1, southern perimeter of Precambrian shield; 2, limit of Lower Paleozoic rocks; 3, limit of Devonian rocks; 4, limit of Mississippian rocks; 5, potash-brine injection; 6, refinery and chemical-plant waste injection; 7, salt-cavern brine injection; 8, chemical-plant waste disposal into salt caverns; 9, oilfield-brine injection.

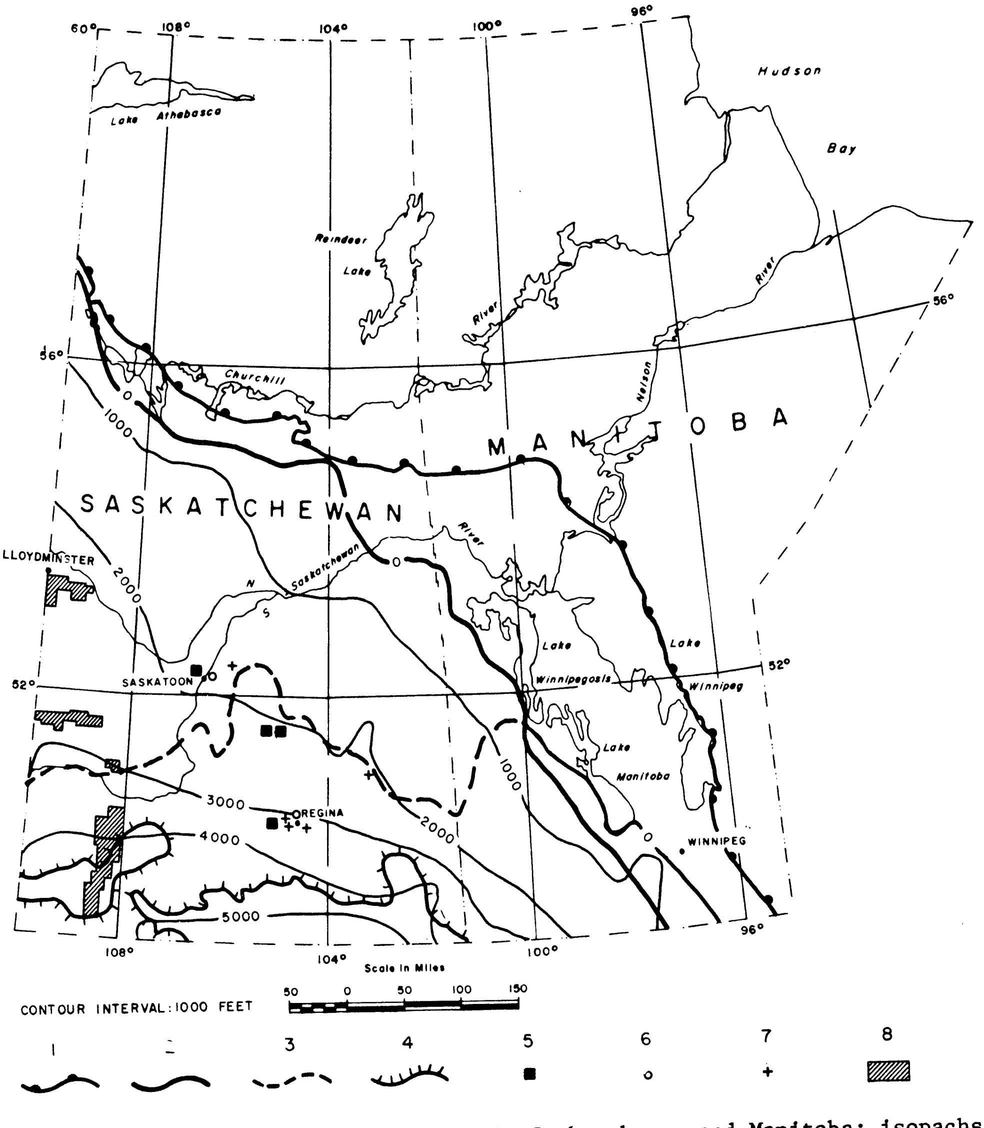


FIG. 11--Upper siliciclastic division in Saskatchewan and Manitoba: isopachs and distribution of subsurface waste-disposal systems. 1, southern perimeter of Precambrian shield; 2, limit of Cretaceous rocks; 3, limit of Jurassic rocks; 4, limit of Cenozoic rocks; 5, potash-brine injection; 6, refinery and chemical-plant waste injection; 7, salt-cavern brine injection; 8, oilfield-brine injection.

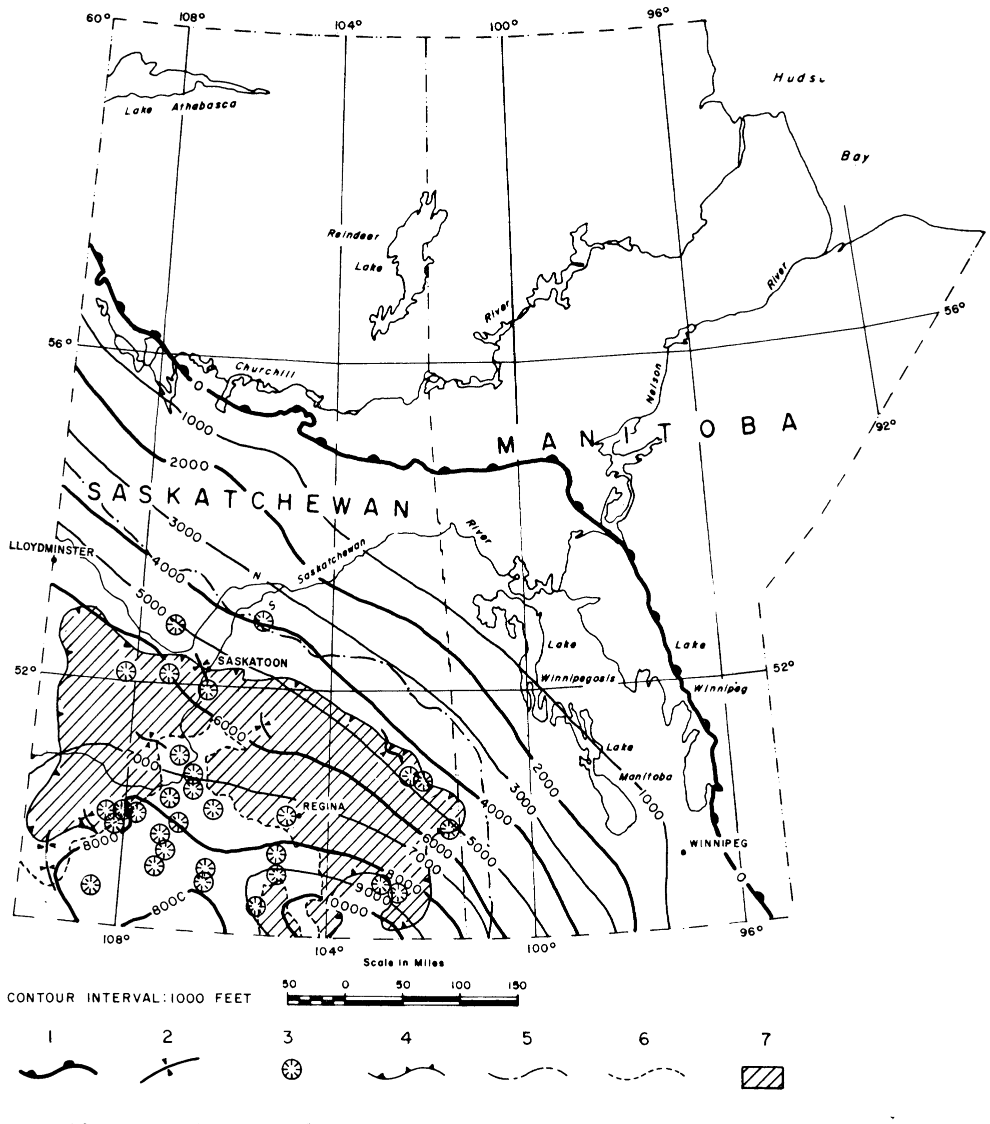


FIG. 12--Distribution of salt-solution and large-scale, circular strıctures, Saskatchewan and Manitoba. 1, southern perimeter of Precambrian shield; 2, linear solution features; 3, sinks and large-scale, circular structures; 4, limit of soluble potassium minerals; 5, limit of salt; 6, area where Prairie Evaporite absent; 7, area of potash production potential.

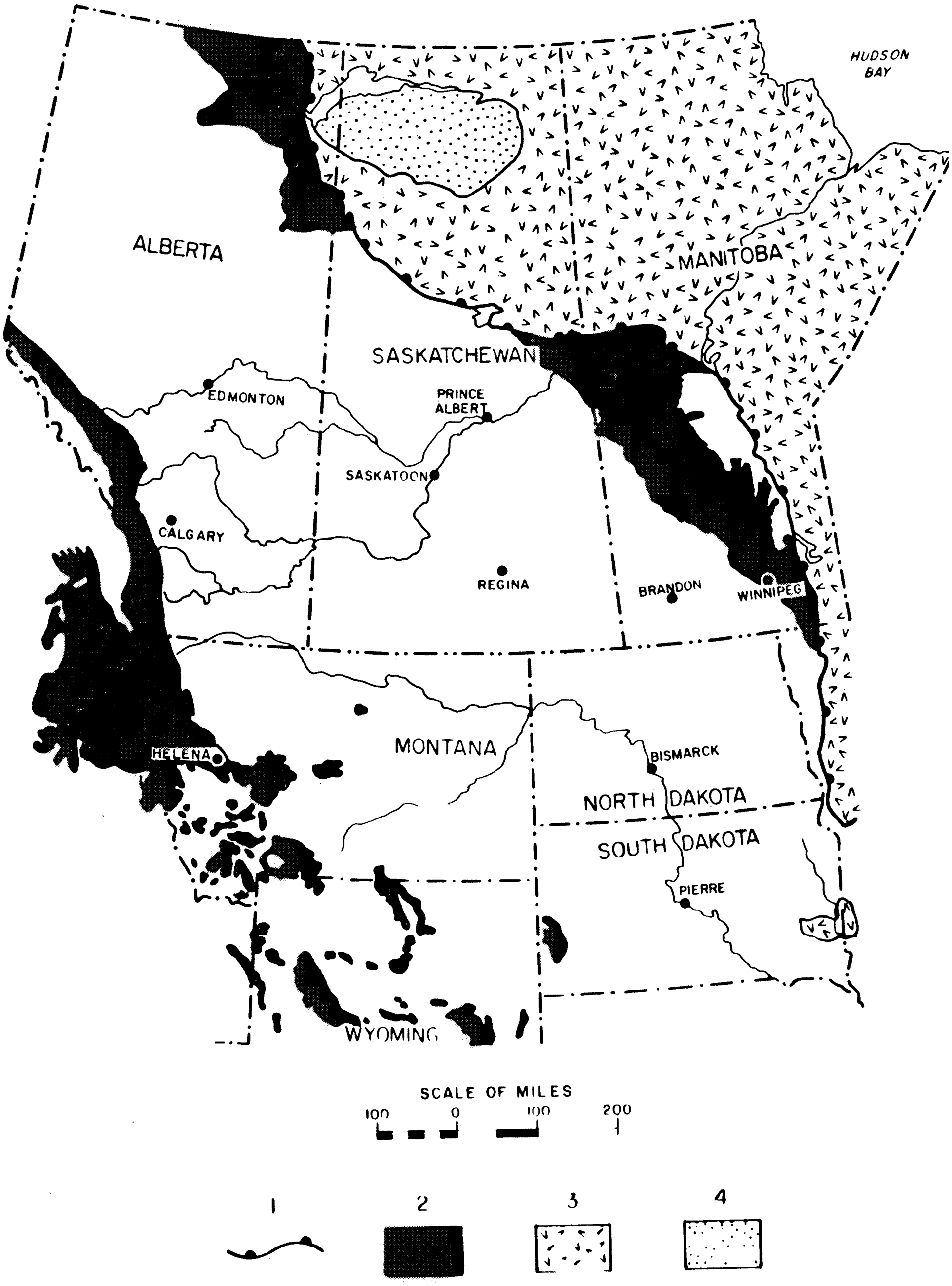


FIG. 13--Outcrop belts of Paleozoic rocks in Williston basin region and adjacent areas. 1, southern perimeter of Precambrian shield; 2, Paleozoi rocks exposed; 3, Precambrian rocks exposed; 4, Athabasca basin.

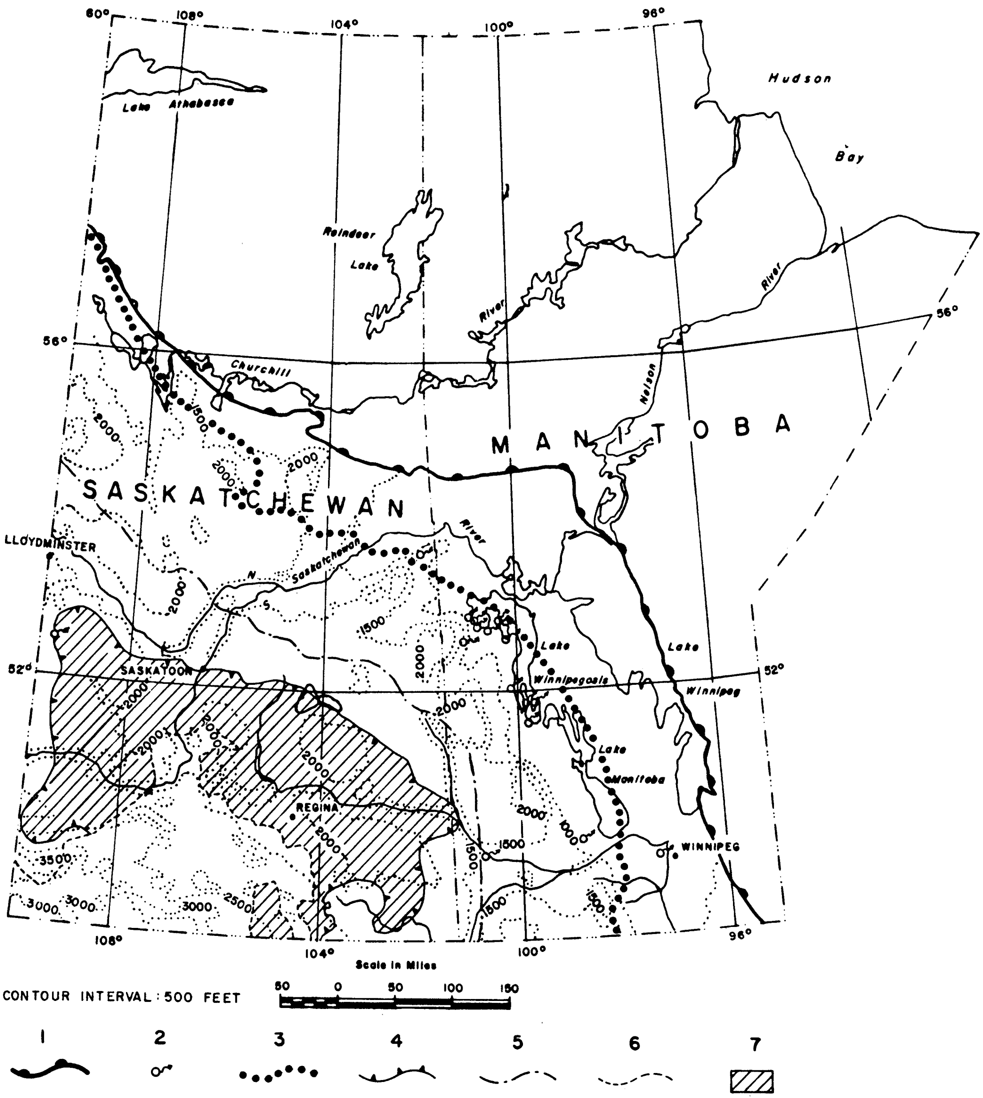


FIG. 14--Saline-spring discharge in northern Williston basin region, Saskatchewan and Manitoba. 1, southern perimeter of Precambrian shield; 2, saline spring; 3, limit of Devonian rocks; 4, limit of soluble potassium minerals; 5, limit of salt; 6, area where Prairie Evaporite absent; 7, area of potash production potential.

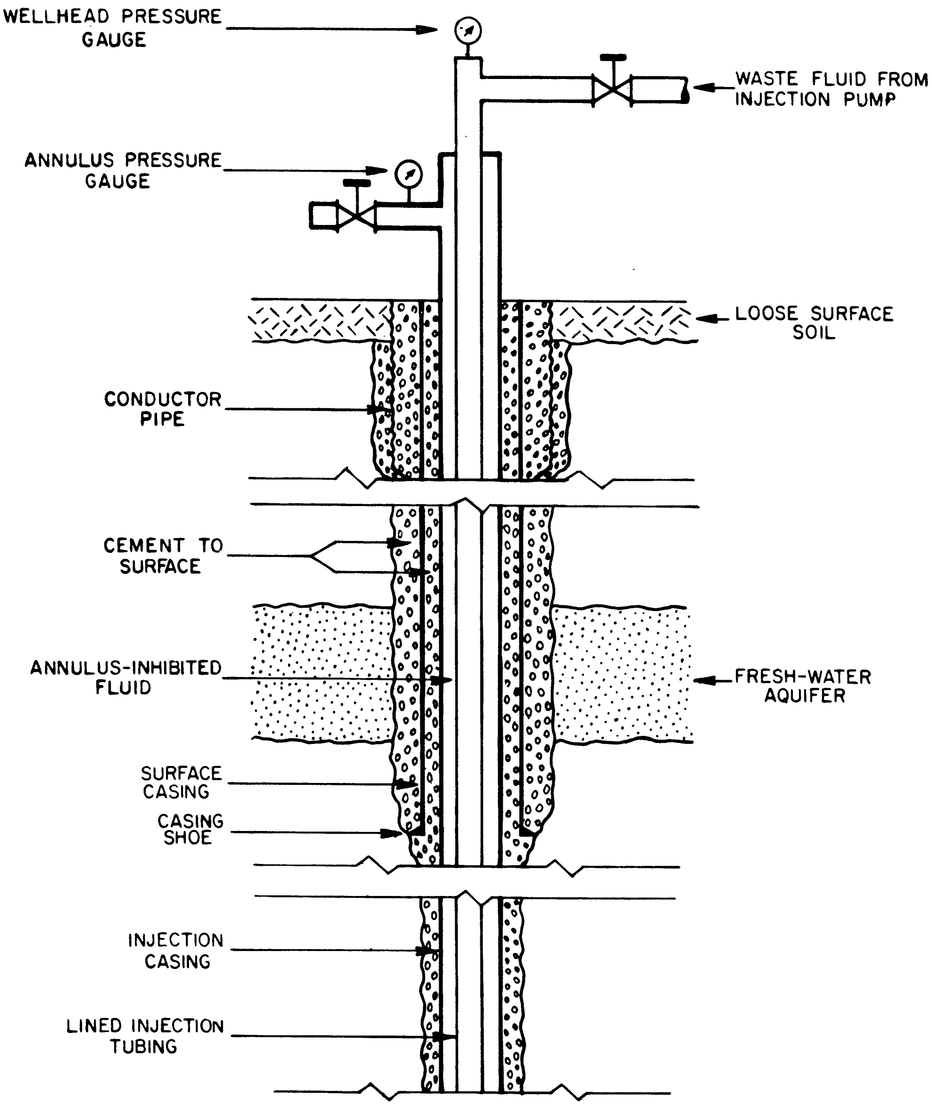


FIG. 15--Typical casing strings and wellhead used in a waste-disposal well.

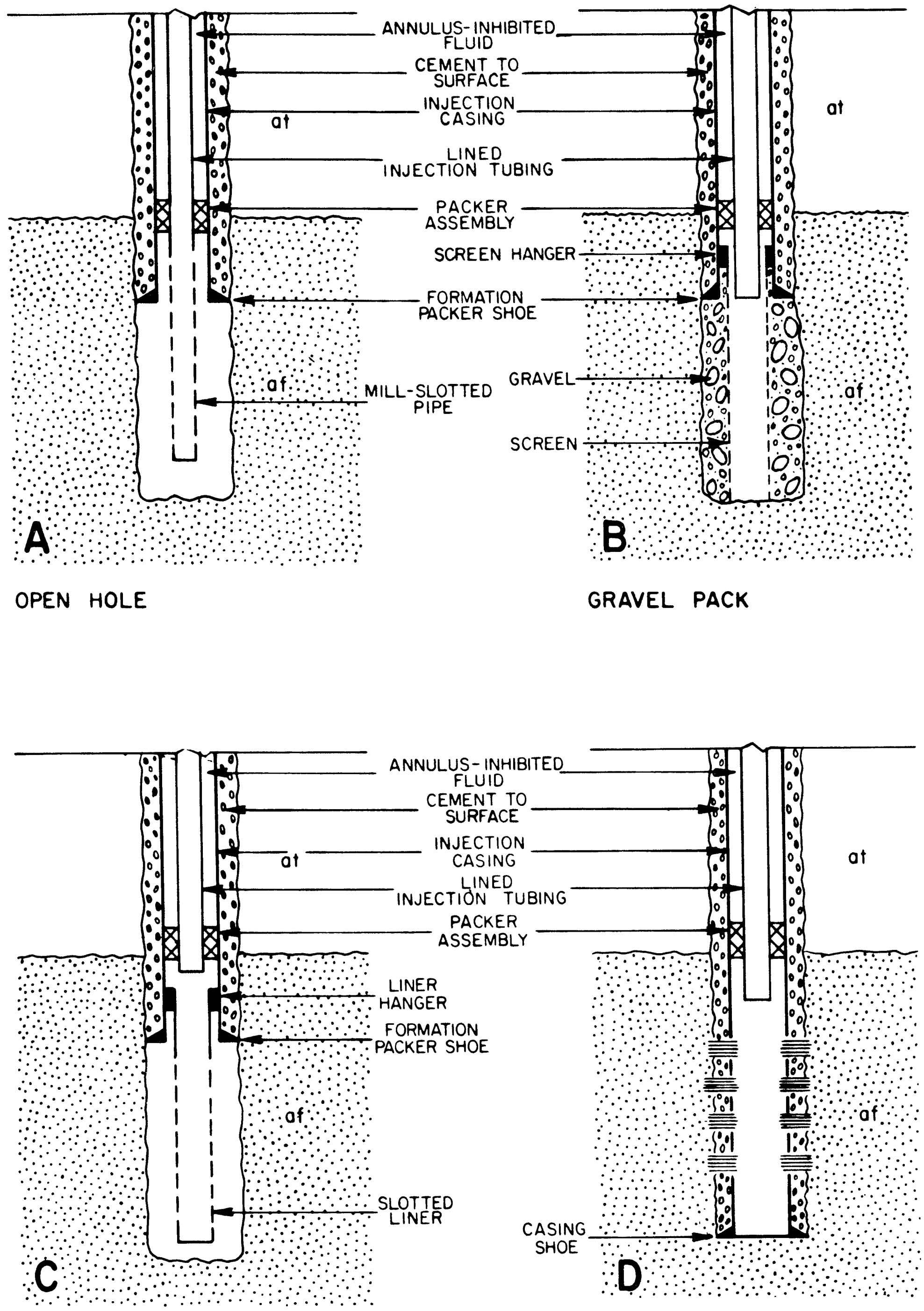


FIG. 16--Options for disposal-well completion.