SUBSURFACE DISPOSAL OF WASTES IN MANITOBA

I - CURRENT STATUS AND POTENTIAL OF DEEP-WELL DISPOSAL OF FLUID, INDUSTRIAL WASTES IN MANITOBA

by

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ABSTRACT

In recent years, deep-well injection has been adopted increasingly in Canada as a means of isolating liquid, industrial wastes from the biosphere to minimize pollution hazard. Subsurface strata with good reservoir quality and potential for receiving fluid, industrial wastes occupy 2 main areas in Manitoba:

(1) the southern part of the Hudson Bay basin region in northeastern Manitoba, where over 2,900 feet of Ordovician, Silurian and Devonian strata occur below the surface onshore; and

(2) the northeastern part of the Williston basin region in southern Manitoba, where beds, ranging in age from Cambrian Ordovician to Tertiary, attain a maximum thickness of about 7500 → 6800 8,000 feet in the extreme southwest.

The stratigraphic succession of the southwestern Hudson Bay basin region comprises 2 main sequences of limestones, dolomites and minor evaporites, Middle Ordovician to Middle Silurian and Lower to Middle Devonian in age respectively, separated by Upper Silurian through Lower Devonian dolomites, fine-grained red beds and subordinate evaporites. Greater lithologic variation is encountered in the northeastern Williston basin region, where the

succession is characterized by 3 main divisions:

(1) a lower clastic division, consisting of the Middle Ordovician Winnipeg Formation, which reaches a maximum thickness of about ~~350~~ 225 feet;

(2) a carbonate-evaporite division, Middle Ordovician through Mississippian in age, which includes an important potash-bearing unit, the Middle Devonian Prairie Evaporite, and has a maximum thickness of about 4,000 feet; and

(3) an upper clastic division, Triassic (?) - Jurassic through Recent in age, which incorporates evaporite strata near the base and reaches a maximum thickness of about 3,500 feet.

Currently, 4 main types of waste undergo disposal into the subsurface strata of southern Manitoba:

(1) Brines withdrawn during commercial production of crude oil have been injected back into Mississippian oil-reservoir strata at depths of 2,010 to 3,270 feet below surface in both pressure-maintenance and disposal wells of the field districts in the southwest since 1953.

(2) Spent caustic wastes from the Imperial Oil Enterprises Limited oil refinery in Winnipeg were injected at low rates and pressures into carbonate reservoir strata of the Lodgepole Formation (Mississippian) at 2,080 feet in a reworked oil-producing well of the Maples field from

1969 to 1975.

(3) Spent cooling water from air-conditioning systems in theatres and restuarants and from cold-storage plants in central Winnipeg is injected back into the Palaeozoic carbonate aquifer, which has served these facilities since 1919.

(4) Low-, medium- and high-level, solid, radioactive wastes and subordinate amounts of liquid, radioactive wastes from the Whiteshell Nuclear Research Establishment have been stored since 1964 at depths of up to 15 feet in Pleistocene clay and till, resting on glacial sands, which overlie Precambrian bedrock near the plant. Disposal of wastes underground in southern Manitoba is carried out in areas of extremely good well control, reflecting development drilling in the oil-production locales and test drilling at Whiteshell respectively. Thus many of the uncertainties, inherent to the underground waste-management decision system and in particular those relating to reservoir geometry of the disposal formation and flow patterns of formation fluids, are largely eliminated.

Biohermal deposits and unconformity-related stratigraphic traps in beds ranging in age from Middle Ordovician to Middle Silurian could be considered in future for waste injection or, alternatively, for aquifer storage of natural gas or even fresh water prior to municipal or industrial use in the Manitoba onshore part of the Hudson Bay basin region. However, the need for such facilities in this remote area is not yet foreseen. In southern Manitoba, on the other hand, diversified industrial development and the presence of several deep aquifers with subsurface-disposal potential ensure immediate interest in deep-well injection as a possible waste-disposal option. The aquifers with greatest potential for receiving industrial wastes are sandstones of the Ordovician Winnipeg Formation and biostromal carbonates of the Silurian Interlake Group at sites restricted to the southwestern corner of the province. Grouting of noxious wastes in Winnipeg shales and storage in specially excavated caverns in Middle Devonian evaporite beds remain possibilities to be considered, but further research is needed. Waste injection into oil-reservoir strata of the production districts through suspended oil wells is worthy of close consideration, because of the detailed subsurface information, available at these locales. Potentially adverse, hydrogeologic factors, which may control the migration of wastes in parts of southern Manitoba, are:

(1) proximity of an outcrop belt to the north and east, where Ordovician through lowermost Upper Devonian and Mesozoic strata are exposed near the southern perimeter of the Precambrian Shield;

(2) the existence of valley systems, incised at the sub-Mesozoic unconformity, which have controlled later development of fluvial valley systems up to the present and give anisotropy of ground-water flow;

(3) fracture-bounded sinks, formed through localized solution of Middle Devonian evaporite beds, which may constitute conduits for easy upward movement of waste fluids under pressure;

(4) positive basement features and related overlying structures, which may deflect waste streams upward; and

(5) the possible existence of a small number of improperly abandoned, old oil-exploration wells, especially in the western part of the province.

In addition, extreme care must be taken to avoid waste contamination of economically important formation fluids, such as crude oil in proven Mississippian and prospective, notably Devonian and Silurian reservoir settings; commercial brines in the Winnipeg and Winnipegosis Formations; and potable ground water in bedrock aquifers, for example, that of Ordovician and Silurian carbonate aquifers, which is a source of water supply for metropolitan Winnipeg.

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1. INTRODUCTION

1.1 General Statement

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

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[1]F. Simpson, 1975, Possible impact of deep-well injection of fluid, industrial wastes on environmental quality in Canada: paper presented at the First Chemical Congress of the North American Continent (Primer Congreso de Química del Continente de América del Norte), Mexico City,

Nov. 30 - Dec. 5, 1975.

Currently in Manitoba (Fig. 1), 4 main types

Fig. 1 - Location map showing distribution of Phanerozoic sediments in Manitoba

of waste undergo disposal into the subsurface strata of the southern part of the province:

(1) Brines withdrawn during commercial production of crude oil have been injected back into Mississippian oil-reservoir strata at depths of 2,010 to 3,270 feet below surface in both pressure-maintenance and salt-water-disposal wells of the field districts in the southwest since 1953.

(2) Spent caustic solutions from the Imperial Oil Enterprises Limited oil refinery in Winnipeg were injected at low rates and pressures into carbonate reservoir strata of the Lodgepole Formation (Mississippian) at 2,080 feet in a reworked oil-producing well of the Maples field from 1969 to 1975.

(3) Spent cooling water from air-conditioning systems in theatres and restuarants and from cold-storage plants in central Winnipeg is injected back into the Palaeozoic carbonate aquifer, which has served these facilities since 1919.

(4) Low-, medium- and high-level, solid, radioactive wastes and subordinate amounts of liquid, radioactive wastes from the Whiteshell Nuclear Research Establishment of Atomic Energy of Canada Limited have been stored since 1964 at depths of up to 15 feet in Pleistocene clay and till, resting on glacial sands, which overlie Precambrian bedrock near the plant.

Tables 1 and 2 summarize the characteristics

Table 1 - Generalized characteristics of wastes at subsurface disposal systems in Manitoba

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Table 2 - Operational status of subsurface-disposal systems in Manitoba to end of year 1975

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of wastes and operational status of subsurface-disposal systems in Manitoba.

1.2 Subsurface-Disposal Objectives

The prime objective of subsurface waste disposal is to emplace undesirable, often noxious substances into goelogic settings remote from the biosphere, thus minimizing the hazard of pollution of potable water. Such geologic settings are provided by 3 mainttypes of subsurface space:

(1) artificial caverns and excavations, such as disused mine workings and salt caverns, as well as shallow pits and trenches in glacial drift;

(2) the natural porosity-permeability distribution of subsurface strata of good reservoir quality, which on occasion may be augmented by hydraulic fracturing or acidization of the rocks; and

(3) the artificial porosity-permeability distribution of hydraulically fractured aquitard or aquiclude strata, usually shales.

Natural pore space is the subsurface-space category most frequently utilized by industrial operators in Canada and is that most entensively discussed in the present account.

The main premises, on which decisions to inject wastes into deep aquifers are based- are:

(1) The disposal strata undergo elastic deformation in response to the pressure of injection, as the wastes are emplaced.

(2) The displacement of indigenous formation fluids from the disposal interval into other strata by the injected wastes is only minor.

(3) The injected wastes may be either contained at a specific location within the disposal strata or confined to, but able to flow within the disposal aquifer away from where the unit is penetrated by the disposal well.

Simpson and Dennison (1975) discussed the need for rigorous, step-by-step analysis of subsurface-disposal decisions, similar to the stages of decision analysis, elaborated by Ellis and Keeney (1972), to minimize the danger of temporary solution of a disposal problem through creation of a long-term pollution problem. Figure 2

Figure 2 - General model for evaluation of regulations controlling subsurface disposal of fluid wastes

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shows a general model for design and evaluation of a system of regulations to control subsurface disposal of fluid wastes. This model is adopted from one discribed by Ellis and Keeney (op. cit.), who considered a problem of air pollution and stressed the need to take into account undesirable "output" in policy formulation. The undesirable "output" of subsurface disposal is possible adverse effects on both health of residents of the province and economy of the province and in each case has to do with escape of wastes from the disposal formation into the biosphere. These possible adverse effects are of utmost importance to any attempt to specify major sub-objectives (Fig. 3) in a disposal program.

Fig. 3 - Major objectives of the subsurface-disposal decision system

All sub-objectives, save the one, relating to an "acceptable political solution", may be translated into capital expenditures, which provide measures of effectiveness of the disposal program. Clearly these effectiveness measures are relevant, when a potential pollution problem exists, and a preferable altermative approach is to closely monitor disposal operations, possibly with a view to shutting down the facility, if a pollution threat becomes imminent.

1.3 Measures of Subsurface-Disposal Effectiveness

Effectiveness of a subsurface-disposal strategy is only ascertained through careful monitoring of operations, by obtaining a continous record of all responses to waste disposal:

(1) The possibilities of leakage of the disposal well and anomalons movement (or lack of movement) of wastes in the disposal formation are checked by continuous observation of (a) injection rate, (b) injection pressure and (c) annular pressure.

(2) Near-surface aquifers are checked for contamination by injected wastes by means of shallow observation wells,

usually drilled to the deepest fresh-water aquifer.

(3) The rate of movement of the plume of injected wastes within the disposal strata is monitored by means of observation wells, drilled to the disposal units.

(4) Increases in strain rate and changes in land elevation near a disposal facility are detected by precise geodetic surveys.

As discussed below, Manitoba has a good record of monitoring subsurface-disposal operations. Disposal at the Whiteshell disposal site is monitored continuously through a variety of barehole, gepphysical and geochemical techniques. In the other 3 cases, the disposal aquifers are in use, in that fluids are withdrawn from them for commercial purposes and any deleterious, disposal-related changes in the aquifers would be readily detected.

1.4 Legal Considerations

There is no legislation in Manitoba, designed specifically for the regulation of subsurface-disposal procedures. Fluid injection, associated with the production of crude oil in the form of salt-water disposal and pressure-maintenance operations, is regulated in accordance with the Mines Act of 1970 and subsequent amendments to the Act. The Clean Environment Act of 1971 was conceived for control of waste emission or discharge into air and water and has some general application to the modes of disposal discussed above. Administration of these regulatory acts is by the Manitoba Department of Mines, Resources and Environmental Management, that is, by the Mines Branch and the Environmental Protection Branch respectively.

1.5 Scope of Study

The present account is a survey of the current status of subsurface waste disposal in Manitoba and places special emphasis on the emplacement of fluid, industrial wastes into confined aquifers by means of injection down deep wells. The potential of the area to support additional waste-injection systems without deterioration of environmental quality is also discussed with reference to both the general hydrogeologic setting of the area and experience of subsurface waste disposal in adjacent areas. This report is the first of 2 papers, prepared as parts I and II, under the title, Subsurface Disposal of Wastes in Manitoba; part II is a detailed, case-history account of deep-well injection of refinery wastes at the Maples oil field. The study utilizes non-confidential information from the files of the Manitoba

Department of Energy, Mines and Environmental Management.

2. REGIONAL GEOLOGY

2.1 General Statement

Subsurface strata with good reservoir quality and potential for receiving fluid industrial wastes occupy 2 main areas in Manitoba:

(1) the southern part of the Hudson Bay basin region of northeastern Manitoba, where over 2,900 feet of Ordovician, Silurian and Devonian strata occur below the surface onshore; and

(2) the northeastern part of the Williston basin region in southern Manitoba, where beds, ranging in age from Ordovician to Tertiary, attain a maximum thichkness of about 8,000 feet in the southwestern corner of the province.

The Hudson Bay basin region of northeastern Manitoba consists of poorly drained, tree- and muskeg-covered lowland, accessible for ground travel only during the winter freeze-up. The area, together with the neighboring onshore region of northern Ontario and the basin proper in Hudson Bay, is regarded as an important frontier of petroleum exploration (Sanford and Norris, 1973). Only xx wells have been drilled in the Manitoba part of the region and, although several significant test results have been obtained from wells drilled south of Churchill, no hydrocarbon production has yet been obtained. Although this remote region has potential for development of waste-injection systems, no plans to initiate such operations are foreseen at present.

The northeastern Williston basin region of southern Manitoba is characterized by an agriculture-based economy throughout much of the area, with important production of light and medium crude oil from Mississippian carbonate reservoirs in the southwestern corner of the province and a diversified industrial economy in the Winnipeg district. Subsurface disposal of wastes, as currently practiced in Manitoba, is restricted to this region. This part of the province has considerable potential for initiation of new subsurface-disposal operations, in that the thick sedimentary sequence incorporates a wide variety of structural-stratigraphic-trap configurations of strata, which might constitute disposal aquifers. Furthermore, southeastern Manitoba's expanding industrial economy provides a potential source of fluid wastes for deep-well injection; also, in the event of southwestern Manitoba coming into its own as a potash-producing district, subsurface-disposal of waste brines will take on considerable importance in the area.

2.2 Physiography

Manitoba occupies a total area of some 250,000 square miles and is divisible into 4 main physiographic regions, each characterized by features, which closely reflect the nature of the underlying bedrock (Davies et al., 1962):

(1) The Manitoba escarpment is an upland eastward extension of the Great Plains region, located in the southwestern part of the province. The area is characterized by undulating relief and includes Baldy Mountain, which has an elevation of 2,727 feet above sea level and is Manitoba's highest point. The region is underlain by Mesozoic clastic rocks and at its eastern limit marks the eastern outcrop edge of several, dominantly argillaceous Cretaceous units.

(2) The Manitoba lowland is bounded to the west by the Manitoba escarpment and to the north and east by the Precambrian Shield and has elevations in the range 700 to 900 feet above sea level. The area is occupied by Lakes Winnipeg, Manitoba, Dauphin and Winnipegosis and intervening, poorly drained land. It is underlain by Palaeozoic carbonate strata.

(3) The Precambrian Shield has elevations of up to 1000 feet above sea level and is characterized by a relatively flat, hummocky surface with relief rarely

exceeding 100 feet. Swamps and lakes are widespread and exposure of Precambrian rocks is good in many parts of the area.

(4) The Manitoba part of the Hudson Bay lowland flanks the southwestern shore of the bay and consists of a poorly drained area of low relief, underlain by Palaeozoic carbonates.

Drainage is into Hudson Bay. The province's major southern rivers (Winnipeg, Assiniboine, Red and Saskatchewan) flow into Lake Winnipeg, which is drained by the Nelson River into Hudson Bay. The Churchill River is the largest river in the province, draining the northern part of the area and also flowing into Hudson Bay.

2.3 Outline of Stratigraphy

The stratigraphic succession of the southwestern part of the Hudson Bay basin region (Fig. 4) comprises 2 main sequences of limestones, dolomites and minor evaporites,

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Fig. 4 - Stratigraphic correlation chart for the Hudson Bay basin region

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Middle Ordovician to Middle Silurian and Lower to Middle Devonian in age respectively, separated by Upper Silurian through Lower Devonian dolomites, fine-grained red beds and subordinate evaporites (Sanford and Norris, 1973).

Considerably greater lithologic variation is countered in the northeastern Williston basin region (Fig. 5), where the succession is characterized by 3

Fig. 5 - Stratigraphic correlation chart for the Williston basin region

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main divisions:

(1) a lower clastic division, consisting of the Middle Ordovician Winnipeg Formation, which reaches a maximum thickness of about 350 feet;

(2) a carbonate-evaporite division, Middle Ordovician through Mississippian in age, which includes an important potash-bearing unit, the Middle Devonian Prairie Evaporite, and has a maximum thickness of about 4,000 feet; and

(3) an upper clastic division, Triassic (?)- Jurassic through Recent in age, which incorporates evaporite strata near the base and reaches a maximum thickness of about 3,500 feet.

2.4 Structure

The Phanerozoic succession of the Hudson Bay basin region occupies two sedimentary and structural basins: The Moose River basin in the south and the Hudson Bay basin in the north, separated by the northeast-trending Cape Henrietta arch (Fig. 6)

Fig. 6 - Structure contours on Precambrian surface, Hudson platform region, onshore northern Manitoba and adjacent Ontario.

The dominant structural element in southern Manitoba is a homocline characterized by a gradual increase in dominantly southwesterly dip of the Precambrian surface from 17 feet per mile near the southern perimeter of the Shield to 50 feet per mile in the southwestern corner of the province. The strike is north-south near the Forty-Ninth Parallel, but undergoes a marked swing to the north-west in the direction of the Saskatchewan border (Fig. 7).

Fig. 7 - Structure contours on Precambrian surface, Williston basin region, Manitoba, Saskatchewan, Montana, North Dakota and South Dakota

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The southwesterly increase in dip of the basement marks the passage from a stable, tectonic shelf to the northeastern flank of the Williston basin proper.

On a local scale, the main factors, controlling the attitudes of beds in the Phanerozoic succession are:

(1) positive relief features of the Precambrian surface;

(2) depressions of successive correlation surfaces, frequently bounded by fractures and related to collapse, following localized solution removal of Middle Devonian evaporite beds; and

(3) Middle Devonian carbonate mounds.

As noted by Simpson and Dennison (1975), the northern Williston basin region is for the most part seismically inactive, although minor tremors have been recorded during the last century. It is noteworthy that seismic recording stations are extremely sparse within the area, the probability that minor earthquakes would pass unnoticed is high.

3. HYDROGEOLOGY

3.1 General Statement

Because fluid wastes, introduced into the hydrogeologic environment of a geologic basin, tend to assume the vector properties of the ground-water regime, waste-injection operations should not be initiated without knowledge of (1) the general distribution of formation-water flow within the principal hydrostratigraphic units, giving deflection from the generalized flow distribution. Deep-well disposal of wastes is frequently characterized by considerable uncertainty (Dennison and Simpson, 1973; Simpson and Dennison, 1975), which is a function of the poor well control with respect to the target aquifer in the vicinity of the disposal site. Subsurface-disposal operations in Manitoba are noteworthy, in that the uncertainty inherent to underground waste management is largely eliminated in each case by the existence of numerous wells, drilled to the disposal strata:

(1) Injection of oilfield brines back into producing Mississippian strata as part of pressure-maintenance and salt-water-disposal operations effected in locales, lithologic variation and flow characteristics is effected in locales, where lithologic variation and flow characteristics of the brine-receiving (and oil-producing) reservoir are well known from numerous, closely spaced wells (McCabe, 1963).

(2) Refinery-waste disposal into Mississippian carbonates at the Maples oilfield was likewise conducted at a relatively high level of subsurface information, owing to the presence of nearby oil producers (Simpson _et al_., in press).

(3) Disposal of spent cooling water into the Palaeozoic Carbonate Aquifer of metropolitan Winnipeg is also at a location of good well control with respect to the disposal (water-producing) aquifer, as demonstrated

by Render's (1970) detailed account of reservoir properties.

(4) The underground waste management site at Whiteshell has been the object of detailed monitoring by means of an extensive pierometer and well network, in addition to test drilling, surface geophysics, short- and long-term pumping tests, single-well response tests, tracer-injection experiments, hydrochemical studies and mathematical simulation of the ground-water flow pattern (Cherry et al., 1973b).

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

Fig. 8 - Distribution of subsurface waste-disposal systems on isopach map of Phanerozoic sequence, southern Manitoba

1 - southern perimeter of Precambrian Shield, 2 - oilfield-brine injection, 3 - refinery-waste injection, 4 - spent-cooling-waste injection, 5 - radioactive-waste disposal.

3.2 Basement Configuration

The Precambrian surface is characterized by a fairly uniform dip of about 17 to 50 feet per mile to the southwest throughout most of southern Manitoba, such that progressively higher values obtained with increasing distance from the Shield edge. The basement configuration is a reflection of both erosion prior to deposition of the lowermost Paleozoic strata and subsequent, tectonic disruption of the surface beneath the sediment cover. As noted by McCabe (1967, 1971), the Precambrian erosion surface exhibits several anomalons areas of departure from the gently southwesterly dip (Fig. 9):

Fig. 9 - Structural features of Precambrian basement with isopachs of Phanerozoic sequence superimposed southern Manitoba

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(1) The Moose Lake syncline is defined by a northeast-trending flexure of structure contours on the basement to the northwest of Lake Winnipeg. The feature is also defined at that location by a northeasterly deflection of the outcrop belts of Ordovician and Silurian rocks, which is indicative of a post-Silurian age. The flexure coincides with the trend of prominent gravity anomalies, which marks the continuation beneath the Phanerozoic cover of the boundary zone between the Churchill and Superior Precambrian provinces. The southern part of this geophysical-anomaly belt is termed the Birdtail-Waskada axis and is the site of numerous structure and isopach anomalies in the overlying

Phanerozoic succession, related to collapse, attendant upon localized solution of Middle Devonian evaporite strata.

(2) In the Hartney area, a pronounced negative relief feature of the Precambrian surface is apparently a consequence of deep, reverse faulting, evidenced by vertical repetition of the Ordovician Red River Formation, located at depths in excess of 100 feet below the regional elevation of the basement. Locally the Red River succession exhibits anomalons thickening of more than 300 feet. The Hartney structure is thought to be not more than 6 to 8 miles in diameter. Some parts of the Upper Devonian succession are missing from the interior of the structure and the top of the Palaeozoic sequence is some 600 feet below the regional elevation. Deformed and brecciated Jurassic (?) sandstones and shales rest on Upper Devonian carbonates. The structure has an uplifted rim, about 250 feet above the regional elevation, which displays intense brecciation of the Palaeozoic carbonates. Haites and Van Hees (1962) suggested that the Hartney structure is a result of movement along a northeast-trending transcurrent fault, but McCabe (1971) favours a crypto-explosion origin for the feature during post-Mississippian, pre-Jurassic time.

(3) The Lake St. Martin structure is approximately

approximately circular crater, about 14 miles in diameter and characterized by relief on the Precambrian surface in the order of 1000 feet or more. Within the crater, a central core area, 2 to 3 miles in diameter, consists of shock-metamorphosed Precambrian gneiss, which has been uplifted about 700 feet. Between the core and a peripheral ring of downfaulted and brecciated Devonian (?) carbonates is a sequence of granite and polymict breccias over 870 feet thick. Aphanitic igneous rocks of trachyandesitic composition occur above and below the polymict breccias. The crater has a rim, in which Lower Palaeozoic and Precambrian rocks have been uplifted by 700 feet or more; the total diameter of the structurally disturbed area is 26 to 28 miles. The crater is thought to have originated as a crypto-explosion phenomenon in late Permian to early Triassic time (McCabe and Bannatyne, 1970).

(4) A Precambrian inlier near Hodgson indicates local relief of the Precambrian surface in the order of 500 feet. It is not known whether this feature is purely palaeotopographic in nature or if Phanerozoic uplift or even crypto-explosion activity were responsible for its formation.

(5) A gently anticlinal flexure of the Precambrian surface extends in an east-west direction to the south

of Winnipeg. The axis of the flexure coincides roughly with the southern edge of the Carman Sand of the Ordovician Winnipeg Formation.

Reactivation of positive Precambrian-surface features during Phanerozoic time has exerted an important influence on the overlying rocks, in the form of structures of variable-scale, affecting deposits Cambrian through Holocene in age. The most important manifestation of this influence is spatial coincidence of belts, characterized by collapse of upper Middle Devonian and younger rocks over sites of localized solution removal of Middle Devonian evaporite strata, and areas of anomalons basement elevation. An important example of such an association of disparate structural features is provided by salt-solution features along the Birdtail-Waskada axis.

3.3 Plaeozoic Strata

The basal clastic division of the northern Williston basin region is represented in Manitoba by some 10 to 225 feet of marine mudstones and sandstones, referable to the Middle Ordovician Winnipeg Formation. In a narrow belt, extending from the Meadow Lake escarpment in central Saskatchewan to the Forty-Ninth Parallel at the Manitoba border, the Winnipeg Formation rests unconformably on the glauconitic sandstones and micaceous shales of the Middle to Upper Cambrian Deadwood Formation. In Manitoba, however, the Ordovician clastics rest unconformably upon weathered Precambrian basement. A few feet of basal conglomerate and medium-grained, quartzose sandstone are succeeded by micaceous mudstones, which are replaced vertically by interbedded mudstones, siltstones and sandstones in the extreme south. Farther north, the mudstones incorporate progressively higher proportions of relatively coarse-grained material, in the form of sandstone and siltstone intercalations, so that the most northerly occurrences of the formation consist of sandstones with only subordinate, interbedded shales. The upper part of the succession incorporates an extensive body of sandstone (the Carman Sandstone), up to 100 feet thick and 80 miles wide, extending for over 150 miles in an east-west direction from the part of the outcrop belt to the east-south-east of Winnipeg. From the forgoing it is clear that reservoir quality in the basal clastic division improves progressively northwards and locally in the vicinity of the Forty-Ninth Parallel eastwards. Figure 10 shows ispoachs of the Winnipeg Formation in southern Manitoba.

Fig. 10 - Isopachons map of the basal clastic division in southern Manitoba

The Winnipeg clastic sequence is thought to be conformably overlain by carbonates of the Red River Formation, which is the basal unit of the carbonate-evaporite division.

The total dissolved solids in formation brines of the basal clastic division attain maximum concentrations near the Saskatchewan border in excess of 250,000 ppm, with a gradual decrease in concentration westwards towards the outcrop belt (Bannatyne, 1960); this is shown in Figure 11. Likewise the highest chloride contents of

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Fig. 11 - Total dissolved solids in brines of the basal clastic division in Manitoba

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formation waters (greater than 200,000 mg/l chloride) are encountered in the Williston basin proper (Porter and Fuller, 1959; Hitchon, 1964) are flanked by progressively smaller values (Fig. 12)

Fig. 12 - Chloride content of brines in the basal clastic division in Manitoba

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The carbonate-evaporite division (Middle Ordovician to Silurian; Middle Devonian to Mississippian) overlies the basal clastic sequence in southern Manitoba and onlaps the Precambrian basement in the central part of the province. The sequence has a maximum thickness of more than 4,000 feet in the southwest and wedges out to the north and east, where the minimum thickness beneath a cover of Mesozoic deposits along its truncated edge is between 100 and 1,700 feet (Fig. 13). The rocks reflect

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Fig. 13 - Isopachous map of the carbonate-evaporite division in southern Manitoba

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sedimentation in a variety of marine, depositional environments. A major unconformity between the Silurian and Devonian Systems represents a hiatus from latest Silurian to early Middle Devonian time and is marked by red beds and local occurrences of anhydrite. Several local and intrabasinal hiatuses are recorded in the carbonate-evaporite division, especially in the Devonian succession, where they are likewise marked by argillaceous red beds. Vertical continuity of the Palaeozoic carbonates is thus 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 most important evaporite deposit is the Middle Devonian Prairie Evaportie, made up of halite, sylvite, sylvinite and carnallite, which attains a maximum thickness of 450 feet in the vicinity of the Saskatchewan border (Figs. 14 and 15). This evaporite sequence is exploited commercially in Saskatchewan for

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Fig. 14 - Isopachous map of the Prairie Evaporite (Middle Devonian) in southern Manitoba

Fig. 15 - Stratigraphic cross-section showing potash strata in the Prairie Evaporite (Middle Devonian) in southern Manitoba

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its potash minerals and halite, but as yet is not mined in Manitoba.

Figures 16 and 17 show variation in total dissolved

Fig. 16 - Total dissolved solids in brines of the carbonate-evaporite division in Maniboba

Fig. 17 - Chloride content of brines in the carbonate-evaporite division in Manitoba

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solids and chloride content respectively for formation brines of the carbonate-evaporite division in southern Manitoba. In both cases, the highest concentrations appear to be localized in the southwestern corner of the province and lower values become progressively more numerous in the direction of the outcrop belt. The carbonates of Middle

Ordovician to Middle Devonian age, which occur at the surface or underlie unconsolidated surficial deposits over about 20,000 square miles of central-south Manitoba, constitute the most extensive and important aquifer in the province, known as the Carbonate Aquifer (Render, 1970; Saskatchewan-Nelson Basin Board, 1972a, 1972b). The Carbonate Aquifer is an example of a hydrostratigraphic unit (Maxey, 1964) with little correspondence between aquifer boundaries and lithostratigraphic boundaries, since the most active zone, in terms of ground-water movement and storage, is the upper 100 feet of the aquifer. The dissolved-solids content of ground water in the aquifer is generally 300 to 600 ppm, but increases to 2,500 ppm near the western aquifer boundary; higher mineralization is also encountered in deeper zones within the aquifer.

In the Manitoba onshore portion of the Hudson Bay basin region, a Palaeozoic carbonate-evaporite sequence (Sanford and Norris, 1973) comprises:

(1) biohermal carbonates, resting on a thin basal sandstone and succeeded by limestones with interbedded, minor dolomites, evaporites and biohermal deposits (Middle Ordovician through Middle Silurian);

(2) dolomites, fine-grained red beds and interbedded, subordinate evaporites (Upper Silurian through Lower

Devonian); and

(3) biohermal carbonated, evaporites (Lower to Middle Devonian).

Drilling in the area is at an early reconnaissance level and little is known about facies relationships and variation in composition of formation waters.

3.4 Mesozoic Strata

The upper clastic division consists of Triassic (?) -Jurassic, Cretaceous, Tertiary and Quaternary detrital deposits and rests with angular unconformity on the carbonate-evaporite sequence in southern Manitoba. The upper clastic sequence attains a maximum thickness of about 3,500 feet in the southwestern corner of the provinces. (Fig. 18).

Fig. 18- Isopachous map of the upper clastic division in southern Manitoba

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The basal deposits of this division are Triassic (?) -Jurassic red, argillaceous sandstones, succeeded by a sequence, made up of anhydrite, dolomite and dolomitic limestone. The anhydrite has been largely converted to gypsum near the outcrop belt. These strata are overlain by interbedded limestone, dolomite, shale and subordinate, calacareous sandstone, which give way in vertical sequence to interbedded shales and fine-grained sandstones, all being of Jurassic age. Lacustrine-fluviatile, fluviomarine and marine sandstones and shales and interbedded lignite form a basal Cretaceous sequence (Swan River or Mannville Group), which rests unconformably upon Jurassic, Mississippian, Devonian, Silurian and Ordovician strata in order of appearance at the erosion surface both northward and eastward. A number of Cretaceous outliers exists, where Mannville-Swan River clastiss occupy sharply defince channels, incised into older strata (Bannatyne, 1971; McCabe, 1971), as shown in Fig. 19.

Fig. 19 - Channel with Mannville-Swan River fill, truncating Jurassic deposits, near Ste. Rose du Lac, southern Manitoba

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The maximum thickness, attained by the Mannville-Swan River succession in Manitoba, is about 400 feet in a deeply incised channel south of Pierson. These doposits are overlain by Cretaceous, marine shales, which attain a maximum thickness in the order of 2,000 feet and are referable to the Ashville, Favel, Vermilian River and Ridiny Mountain Formations, in order of decreasing age. Strata of good reservoir quality in this succession are largely restricted to the Ashville Sand in the lower part of the Ashville Formation, which occurs as a blanket sand, less than 20 feet thick, in the southwest. Near Virden, however, the Ashville Sand occupies a prominent channel with a trend parallel to the Ashville strike (northwest to southeast) and locally attains a thickness of 120 feet (Bannatyne, 1970; McCabe, 1971). Improved reservoir quality is also obtained in up to 150 feet of sands and sandstones and interbedded, kaolinitic shale, referable to the uppermost Cretaceous unit, the Boissevain Formation, which is exposed on Turtle Mountain in the southwest.

Variation in total dissolved solids and chloride content in the upper clastic division (Mesozoic and Cenozoic strata) is presented in Figures 20 and 21 respectively.

Fig. 20 - Total dissolved solids in brines of the upper clastic division in Manitoba

Fig. 21 - Chloride content of brines in the upper clastic division in Manitoba

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3.5 Cenozoic Strata

Tertiary deposition in the area is evidenced by at least 480 feet of sandstone, unconsolidated sand, silt and clay with interbedded lignite, concentrated particularly at the base, and limonitic (?) concretionary layers, all referable to the Turtle Mountain Formation (Bannatyne, 1970; Bamburak, 1971). This unit is restricted to the Turtle Mountain area third prairie level of southwestern Manitoba, which rises to an elevation of 2,500 feet, some 800 feet above the surrounding plains second prairie level and is regarded as a geologic and topographic outlier of the Missouri Coteau of Saskatchewan and North Dakota. Lignite at the base of the unit suggests possible age equivalence with the Palaeocene Ravenscrag Formation of Saskatchewan.

Quaternary deposits in southern Manitoba are generally 100 to 200 feet thick and attain a maximum thickness of the order of 1000 feet. These unconsolidated sediments consist mainly of Pleistocene till and clay, which underlie, incorporate and overlie extensive, though subordinate of deposits of glaciofluvial sand and gravel. The most extensive sand and gravel deposit in the province is the Assiniboine delta aquifer, which occupies an area of 800 square miles to the east of Brandon and has an overage saturated thickness of 50 feet (maximum value of 100 feet). In addition, a number of smaller, poorly known, "secondary" aquifers have been recognized in southern Manitoba (Saskatchewan-Nelson Basin Board, 1972a, 1972b). For the most part, these are sand and gravel deposits, for which single-point yields of potable water could exceed 1 cfs. The largest of these aquifers are located over about 500 square miles of the Agassiz and Sandilands Provincial Forest areas about 300 miles of the glacial Lake Souris basin region, west of the Souris River between Melita and Oak Lake. Some 15 or more sand-and-gravel aquifers are interbedded with till, located in buried bedrock valleys and coincident with major, modern river valleys. The average thickness of the drift is about 200 feet, but actual thicknesses vary from values in the range 600 to 1000 feet on the Duck Mountain upland to between 10 (or less) and 500 feet on other uplands and adjacent plains (Klassen, 1971). The distribution of the main drift aquifers in southern Manitoba is shown in Figure 22.

Fig. 22 - Main drift aquifers in southern Manitoba

3.6 Major Unconformities

A briel discussion of the major unconformities, recorded from the stratigraphic succession in Manitoba, is presented below, with some emphasis on the lithologic features, likely to control the cross-formational flow of subsurface fluids, which in future might incorporate injected-waste streams. The most pronounced unconformity is the Phanerozoic-Precambrian nonconformity, which is taken to be the lower physical limit of subsurface fluid flow in the western Canada sedimentary basin as a whole. The present configuration of the Precambrian surface is a record of the topographic relief prior to burial and of all subsequent (post-burial) tectonic activity. Anomalous features of this surface are discussed in Section 3.2 above. The Manitoba part of the western Canada basin is chiefly underlain by the subsurface extension of the Superior province of the Precambrian Shield and the Birdtail-Waskada axis has been taken to mark the boundary zone between the Churchill and Superior crustal blocks. McCabe (1971) has shown that the Manitoba portion of the western Canada sedimentary basin has exhibited anomalous behaviour during Palaeozoic time, which took the form of increased subsidence or increased uplift with respect to the rest of the basin and seems to have been related to a different response of the Superior crustal block to regional tectonic forces, as compared with neighbouring blocks.

Hiatuses in the Palaeozoic succession are marked by fine-grained red beds and local concentrations of anhydrite. The most important of these is the stratigraphic break from Late Silurian to early Middle Devonian time, which is recorded as a sequence of brick-red shale and dolomite, referable to the Middle Devonian Ashern Formation.

The sub-Mesozoic erosion surface (Fig. 23) of

Fig. 23 - Structure contours on the sub-Mesozoic erosion surface in southern Manitoba

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southern Manitoba represents a karstic-trellis topography, developed on Palaeozoic carbonates, which increase in age from Mississippian through Ordovician both northwards and eastwards. Cavernous porosity development is reported from near-surface carbonates of the Souris River Formation (McCabe, 1971). Numerous large solution channels in the Souris River Formation, up to 10 feet by 30 feet in cross-section and of undetermined length, have been uncovered near Mafeking (McCabe, op.cit.; Bannatype, 1975). The channels are filled with fine quartzose sand and clay, probably of Cretaceous age. Conical solution caverns, containing green, orange and brown clays (post-Devonian to Early Cretaceous, have been recorded from the Elm Point Formation at Steep Rock (Bannatyne, op. cit.). Features, such as these and the solution-enlarged joint fissures, noted by Render (1970) in the Palaeozoic Carbonate Aquifer of the Winnipeg district, appear to be typical for the Palaeozoic rocks immediately beneath the Mesozoic-Cenozoic cover. Widespread solution effects near the unconformity will clearly tend to greatly enhance the permeability of the deposits.

Where evaporites and red beds of the Jurassic Amaranth Formation rest upon Mississippian carbonates in southwestern Manitoba, permeability has been affected in a manner completely opposite to that outlined above. The uppermost Mississippian rocks have undergone extensive dolomitization and anhydritization to depths beneath the sub-Mesozoic unconformity, which vary with change in thickness of Lower Amaranth argillaceous red bend, separating the carbonated from the Upper Amaranth evaporites (McCabe, 1959; Young and Greggs, 1975). Dolomitization apparently resulted from downward percolation of hypersaline brines during Upper Amaranth anhydrite deposition, so that the dolomitized Mississippian strata attain greatest thicknesses, where the Jurassic red beds are relatively thin or totally absent. The tight, strongly indurated rocks beneath the unconformity form capping lithologies of Mississippian crude-oil reservoirs in southwestern Manitoba.

McCabe (1971) lists several, relatively large-scale anomalies of the sub-Mesozoic surface:

(1) The Lake St. Martin structure is a prominent feature, approximately Permian age, which was truncated by pre-Jurassic erosion, but subsequently protected beneath a cover of Amaranth strata.

(2) The Hartney structure incorporates disturbed, basal Devonian through Mississippian strata overlain by Jurassic beds, showing signs of disruption, although there is little evidence of deformation in pre-Devonian or post-Jurassic rocks.

(3) Cuestas, scarps and re-entrants have resulted from recessive weathering of shales, notably along the Mississippian edge and along the Virden-Whitewater Lake subcrop.

(4) An east-west-trending channel, south of Winnipeg, has relief in excess of 500 feet and is filled with Jurassic red beds and evaporites, which probably overlap as far east as the Precambrian Shield.

(5) The sub-Mesozoic surface is dissected by small, sharply defined pre-Cretaceous channels, which give rise to outliers of Cretaceous channel fill, as noted above.

(6) Local palaeotopographic elevations are defined by Duperow strata, south of Riding Mountain National Park (relief 200 feet), and Dawson Bay beds at Portage la Prairie (relief 150 feet).

(7) Structural and palaeotopographic anomalies north of Riding Mountain National Park probably result from a combination of salt-solution collapse and Winnipegosis reef growth.

The bedrock topography in southern Manitoba (Klassen *et al.*, 1970; Klassen, 1971) is reflected in the main elements of surface relief. On a regional scale, bedrock relief and surface relief are approximately the same, except on the Duck Mountain upland, where the relief of the bedrock is much less than that of the surface. Bedrock lowlands beneath the Assiniboine delta and Valley River plain are the sites of major preglacial drainage channels. The main features of the bedrock surface are shown in Figure 24.

Fig. 24 - Valley systems at the pre-Quaternary erosion surface in southern Manitoba

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3.7 Salt-Solution Features

Localized solution removal of evaporties strata from the Middle Devonian Prairie Evaporite and attendant collapse of younger deposits have produced numerous structural features in southern Manitoba (Fig. 25). The edge of the

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Fig. 25 - Salt-solution features in southern Manitoba

Prairie Evaporite is believed to represent a solution edge, rather than the limits of evaporite deposition, and the gentle flexure of structure contours along the salt edge is cited evidence for such an origin (McCabe, 1971). Drawdown, associated with major river valleys, is an important effect of topography on fluid flow in bedrock aquifers (Hitchon, 1969a) and may have exerted a profound influence on patterns of salt solution. Hitchon (op.cit.) believes that downward-moving water from the recharge area between the Touchwood Hills and the Maintoba escarpment contributed to the solution of the updip part of the Prairie Evaporite. The largest salt-solution collapse feature in the northern Williston basin region is a roughly triangular, salt-free depression in southwestern and central-southern Saskatchewan (Baillie, 1953). This structure is approximately 23,000 square miles in area and is delimited by a prominent scarp in the northwest and northeast, where younger strata are draped over the present southern salt edge.

Kent (1968) summarized evidence for accelerated solution removal of salt during several discrete intervals from the late Middle Devonian to Late Cretaceous or Early Tertiary time. The earliest solution events (Table 3) gave rise to local channels, which later coalesced to give the present edge of the Prairie Evaporite. Local

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Table 3 - Intervals of accelerated solution removal of bedded salt and attendant collapse of overlying strata, northern Williston basin region

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and regional salt-solution structures are narrow, elongate sinks at correlation surfaces and smaller-scale, subcircular, often fracture-bounded depressions; positive structural features of salt-solution origin include plunging anticlines, which have resulted from the draping of sediments over residual bodies of undissolved salt. The earliest known major period of salt solution in Manitoba is referable to Souris River-Duperow time (early Late Devonian) and is evidenced by anomalous thickness increases in deposits of that age at locales of anomalously thin Prairie Evaporite (McCabe, 1971). Occurrence of a normal sequence in the upper part of the Prairie Evaporite indicates limited solution at the base of the evaporite sequence with access to the salt provided by the Winnipegosis aquifer. Isopach thick trends for the Lyleton-Bakken succession along the Prairie Evaporite salt edge evidence localized solution during latest Devonian and earliest Mississippian time (McCabe, 1971). Collapse of strata following localized solution of the Prairie Evaporite and younger evaporite beds, mostly Mississippian in age, is an important factor controlling structure and sedimentation patterns in overlying deposits, not only in the relatively shallow tectonic shelf of the Williston basin region (De Mille et al., 1964; Christopher et al., 1971, 1973), but also in the deeper setting of the basin proper as discussed by Parker (1967).

Instances of localized salt solution above anomalously thick Winnipegosis sections have been noted (Bishop, 1953). The Winnipegosis carbonate mounds constituted structurally high aquifers below the Prairie Evaporite and solution probably took place along fractures in the salt, formed as a result of compaction above these elevations (Holter, 1969). Formation waters may have been deflected over positive basement relief features so as to migrate vertically up associated fractures in the overlying strata, giving rise to solution of the Prairie Evaporite and related collapse of younger deposits (Wilson et al., 1963).

3.8 Movement of Formation Fluids

Mathematical models of ground-water movement, developed by Tóth (1963, 1963) and Freeze and Witherspoon (1967), assume hydraulic continuity of the ground-water regime and indicate that the distribution of fluid potential and related patterns of motion are strongly influenced by topography and geology. The importance of these factors in controlling fluid-potential distribution in the western Canada sedimentary basin as a whole has been demonstrated by Hitchon (1969a, 1969b).

The overall flow pattern is from southwest to northeast on a basinwide scale and is largely controlled by the reservoir characteristics of the major hydrostratigraphic units 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-Swan River sandstone aquifers. Northeastward movement of water in Palaeozoic strata, accompanied by solution of salt beds, belonging to the Prairie Evaporite, was reported by Milner (1956). The centrol Montana uplift is recognized as being the recharge area for meteoric waters flushing the Palaeozoic succession of southern Saskatchewan (Christopher, 1961). This would readily explain the existence of a northeast-trending corridor of relatively fresh water (less than 94,900 mg/l chloride) in both pre- and early post-Prairie formations, coinciding 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). Fluid migration in a northeasterly direction has been demonstrated in the Interlake Group of the Regina district by Wilson _et al_. (1963). A general updip flow of brines from the Williston basin proper is indicated by the occurrence of relatively high chloride contents of formation brines in successive Palaeozoic units of southeastern Saskatchewan and southwestern Manitoba,

with much lower values obtained in a northeast-trending belt farther north (Hitchon, 1964).

Replenishment of shallow aquifers in southern Manitoba, on the other hand, is for the most part by local introduction of meteoric waters, which seep downwards through glacial deposits overlying the aquifers. For example, the Saskatchewan-Nelson Basin Board (1972b) lists 5 main ground-water flow systems within the Carbonate Aquifer or originating outside the aquifer, but of importance for recharge or for effect on water quality:

(1) A major flow system originates in a high, sandy area east of the Red River with flow toward the river.

(2) Another flow system originates in the Bird Hill area, northeast of Winnipeg.

(3) To the northwest of Winnipeg, system extends from the Lake Manitoba-Lake Winnipeg divide toward Winnipeg and the Red River.

(4) In the area between Lakes Manitoba and Winnipeg, ground water flow in the upper part of the aquifer is from the divide toward the lakes.

(5) In the vicinity of Le Pas, ground-water flow in the aquifer is southward in the direction of the Saskatchewan River.

All major river valleys of the Saskatchewan-Nelson drainage basin constitute important discharge areas (Hitchon, 1969a). In addition, formation brines are discharged from Palaeozoic carbonate strata along the northern margin of the western Canada basin. Saline-spring discharge has been recorded from locations along the southern perimeter of the Precambrian Shield in eastern Alberta (Souther and Halstead, 1969), east-central Saskatchewan (Simpson and Dennison, 1975) and southern Manitoba (van Everdingen, 1971). Carbonate mounds of the Devonian Winnipegosis Formation (McCabe, 1967), exposed along the western shore of Lake Winnipegosis, are the sites of brine discharge in Manitoba (Table 4). According to van Everdingen (1971),

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Table 4 - Chemical composition of brines discharged in saline springs in southern Manitoba

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brines from pre-Devonian units also contribute to the saline waters discharged in this area; the brines, discharged as spring waters and by diffuse seepage over a wide area, are thought to have originated through solution and removal of Middle Devonian evaporites by formation waters in Saskatchewan and Manitoba.

4. SUBSURFACE DISPOSAL OF WASTES

4.1 General Statement

Subsurface disposal of industrial wastes in Manitoba entails confinement and containment of both liquid and solid substances, referable to a narrow range of waste catagories. "Natural" wastes, which in the terminology of van Everdingen and Freeze (1971) include constiuents commonly found in the subsurface, though not necessarily in the disposal aquifer, are represented by the brines, withdrawn together with crude oil and injected back into deep strata in the oilfield district in salt-water-disposal and pressure-maintenance operations. "Foreign" wastes have constituents not normally found in a subsurface setting and in Manitoba, these are refinery spent caustic, injected into 2 Mississippian reservoirs at the Maples oilfield, and low-, medium- and high-level, radioactive wastes, contained in a variety of shallows receptacles in Pleistocene deposits at the Whiteshell Nuclear Reseacch Establishment of Atomic Energy of Canada Limited. The safety record of subsurface-disposal facilities in Manitoba is extremely good and operations are generally well monitored. At present, a major threat to environmental quality in the province is provided by contamination of potable water, not related to underground waste management, but rather to shallow, underground containment of non-waste, refined petroleum products. For this reason, a brief summary of ground-water contamination by refined petroleum products is included in this chapter.

4.2 Oilfield-Brine Injection

The first oil discovery in the Canadian part of the Williston basin region was made in 1951 by the California Standard Company at Daly, where high-gravity crude oil (32^{o} API) was found in carbonates of the Mississippian Lodgepole Formation at a depth of 2,500 feet. Almost all known reserves of crude oil in Manitoba were discovered in the years 1951-1957 in Mississippian carbonates of 14 main fields and at depths of 2,030 to 3,095 feet. Light and medium crude oils are now produced from Lodgepole and Mission Canyon reservoirs, most importantly in the Daly and Virden districts of southwestern Manitoba. The hydrocarbons are trapped in structural-stratigraphic reservoir configurations, involving truncation of the Mississippian oil-producing units at the sub-Mesozoic unconformity (Fig. 26). The

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Fig. 26 - Mississippian erosion surface and distribution of oil fields in southwestern Manitoba

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unconformity surface is overlain by Amaranth (Jurassic) red beds, which together with secondarily dolomitized and anhydritized Mississippian carbonates immediately below the erosion surface, constitute an effective cap rock. Several different types of truncation-trap configuration are described and discussed in detail by McCabe (1959, 1963).

Brines withdrawn during commercial production of crude oil were found to contain 5,000 to 120,000 ppm chloride and efforts were made to contain them in isolation from potable water by storage in shallow, earthen pits and injection into deep, confined aquifers, both Jurassic and Devonian in age. Brines were transported to the disposal sites by means of the pipelines of a specially constructed brine gathering system and by Tank Truck. Furthermore, some wells were dually completed as oil producers and salt-water disposal facilities. In addition, the California Standard Company initiated a pilot waterflood program in late 1953 in the eastern part of the Daly field, where oil wells had suffered a sharp decline in production. The secondary-recovery program was very successful in stimulating an increase in production from these wells and was subsequently expanded to other parts of the field, both through drilling of additional injection wells and conversion of existing producers for water injection. The water for flooding was taken from the brine-disposal gathering systems and also from wells completed in Jurassic units. The brines underwent surface treatment prior to injection. Table 5 outlines

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Table 5 - Oilfield brine injection in southern Manitoba

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the distribution of brine-injection facilities in the oilfield district of southern Manitoba.

4.3 Refinery-Waste Injection

Deep-well disposal of "foreign", industrial wastes in Manitoba is represented by a single facility, operated by Imperial Oil Enterprises Limited for disposal of refinery wastes from October, 1969, to October, 1975. A fairly detailed case history of the disposal well is presented in a separate account by Simpson et al. (in press), which is the source of the following briel summary.

The well is a reworked producer in the Maples oilfield, located some 175 miles west of Winnipeg. The Maples field has obtained production of light crude oil (33°API) from bioclastic limestones of the Whitewater Lake Member and the uppermost part (Upper Virden Unit or "Crinoidal") of the underlying Virden Member of the Mississippian Lodgepole Formation since February, 1955. The field produces from a minor fold of salt-solution origin and occupies an area of 520 acres; it comprises 17 development wells (~~9~~ 7 capable of production, 3 abandoned producers, ~~5~~ 7 dry holes) drilled an 40-acre spacing and 2 brine disposal wells. The average depth of the pay is 2,105 feet below surface and the average aggregate pay thickness is 45 feet, of which about 12 feet is "Crinoidal". The total original oil in place amounted to 10,456,000 bbls., of which ~~724,000~~ 761,000 bbls. were reserves, estimated as recoverable by primary means. The total cummulative production of oil at Maples to December 31, 1974, was 700,515 bbls., with water drive the natural depletion mechanism. The water saturation of the Maples reservoir is 40 percent and the cumulative water production to December 31, 1974, was 9,542,256 bbls. Maples producing wells tend to water out relatively early in their production histories. An example is provided by the Imperial Virden 7-8M-10-26 well (Lsd 7-8-10-26 W 1), which yielded 21,339 bbls. of crude oil and 478,370 bbls. water from March, 1956, to September, 1962, before being suspended as a producer; this well was converted for waste injection in October, 1969, and later that month went on stream as a disposal well.

The Upper Lodgepole strata, which serve as both oil reservoir and disposal aquifer at the Maples locale, occur close to the sub-Mesozoic erosion surface (Fig. 27).

The refinery wastes are contained within the Lodgepole

Fig. 27 - Structure contours on the Lodgepole Formation of the Maples oilfield, southwestern Manitoba

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strata in isolation from commercial oil accumulations as a result of interaction between the following hydrogeologic factors:

(1) the presence of impermeable Lower Amaranth red beds above, as well as dolomitized and anhydritized Lodgepole strata below the sub-Mesozoic unconformity;

(2) facies change in the reservoir strata, which takes the form of progressive westward decrease in grain size, porosity and permeability of both the Whitewater Lake Member and the Virden Member;

(3) the relatively low permeability of the Lower Lodgepole succession and underlying shales of the Bakken Formation;

(4) down-dip penetration of the upper part of the Lodgepole Formation by the disposal well with respect to existing crude-oil production in the Maples field; and

(5) the low injection rates (3.5 US g/m) and injection pressures (o psig) of the disposal system.

The pressure draw-down within the disposal reservoir close to the disposal well, resulting from the pre-injection withdrawal of formation fluids, permitted introduction of wastes at gravity feed and minimized the hazard of inadvertent fracturing of the disposal formation and superjacent impermeable strata.

The wastes were spent caustic solutions from the Imperial Oil Limited refinery in Winnipeg, which were transported by tank truck to the Maples disposal site in quantities averaging about 30 bbls./day. The wastes were rich in phenols relative to sulphides and were produced during refinery neutralization and extraction of acidic contaminants in crude oil and in the products of treatment reactions and cracking operations. Organic compounds, including phenols, made up 12 to 25 per cent of the injected waste by weight, sulphides and mercaptan sulphur 3 to 7 per cent, caustic soda 5 to 10 per cent, and water 58 to 77 per cent. In pre-injection laboratory tests, precipitates were formed, when various types of spent caustic solution were mixed with equal volumes of brine from the Lodgepole Formation of the Maples Field. Between 77.9 and 100.0 per cent by weight of individual precipitate samples were found to be soluble in dilute hydrochloric acid. These tests, therfore, suggested that acidization would be effective in restoring porosity, lost as a result of waste-brine incompatibility in the subsurface environment. The possibility of precipitate formation in the immediate vicinity of the open-hole completion was minimized at the beginning of disposal operations through initial injection of 1,000 barrels of fresh water as a buffer pad. Porosity was restored after plugging in July, 1970, by acidization with 250 gallons of 28 per cent hydrochloric acid, injected at 3 bbls/ min. and 600 psig pressure.

4.4 Spent Cooling Water

Ground water from the Palaeozoic Carbonate Aquifer was utilized by the city of Winnipeg for water-supply purposes from 1900 to 1919, when the Greater Winnipeg Aqueduct was completed. Subsequently, wells were drilled in the central Winnipeg district to supply water for air conditioning in theatres and restuarants and for cold-storage plants, requiring large quantities of cold water during peak operating periods (Render, 1970). A ground-water sewage tax was introduced then to encourage recharge to the Carbonate Aquifer by injection of the spent cooling water. Render (op.cit.) noted that 8 recharge systems were initiated between 1940 and 1960. Return of the warm cooling water into the aquifer has resulted in ground-water temperatures of up to 50°F at some sites within the urban drawndown cone, whereas water temperature elsewhere in the southern part of the aquifer is from 39 to 43°F (Render, op. cit.). It is noteworthy that the Carbonate Aquifer probably contains water at temperatures, close to or at freezing point, in parts of central Manitoba, where permafrost exists (Saskatchewan-Nelson Basin Board, 1972, p. 731). The distribution of cooling-water injection wells, which return the water to the Carbonate Aquifer, is shown in Figure 28.

Fig. 28 - System of return wells for spent cooling water in metropolitan Winnipeg

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4.5 Radioactive Wastes

The subsurface radioactive-waste management facility at the Whiteshell Nuclear Research Establishment (WNRE) of Atomic Energy of Canada Limited (AECL) in southeastern Manitoba (Fig. 29) is one of five such operations in

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Fig. 29 - Underground waste management at the Whiteshell Nuclear Research Establishment, southern Manitoba.

A. Location map. B. Waste-Management facilities

C. West-east cross-section across waste-management site.

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existence[1] in Canada today (Cherry et al., 1973a). The

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[1]The other facilities are at the Chalk River Nuclear Laboratories of Atomic Energy of Canada Limited, Ontario; the Bruce Nuclear Power Development of Ontario Hydro; the Gentilly Nuclear Power Development of Québec Hydro; and

the Defence Research Establishment at Suffield, Alberta.

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waste management site has been in operation since 1964 and receives low-, medium- and high-level solid wastes and subordinate amounts of luquid wastes from experimental reactor operations; from biological, metallurgical and chemical laboratories at WNRE; and from universities and industries in west-central Canada. Disposal is by burial in Pleistocene deposits at depths of up to 15 feet below ground level. These disposal operations (Table 6) do not

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Table 6 - Subsurface disposal of radioactive wastes at the Whiteshell Nuclear Research Establishment, southern Manitoba

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injection of wastes and detailed considerations of them are beyond the scope of this account. The following brief discussion, based on work by Cherry _et_ _al_. (1973b), is included, primarily because of the need to consider all options for disposal of radioactive wastes, in view of the expanding role of the nuclear-power industry in energy supply.

WNRE's waste-management area is about 6 acres of the Canadian Shield, in which granitic Precambrian bedrock is overlain by 30 to 80 feet of drift, consisting of Pleistocene clay, clayey till and sand beneath a soil cover. The radio-active wastes contained within the area are buried below the water table. The main waste constituents are radio-isotopes of uranium, plutonium, strontium and cesium. Low-level wastes account for most of the radio-active materials buried at the WNRE disposal site and are contained in 50 foot by 20 foot trenches, excavated to a depth of 12 ft., covered with clay and till, when full. Concrete sandpipes, 12 ft. deep and 2 ft. in diameter and lined with asphalt or stainless steel, receive medium-level solid and liquid wastes, as well as high-level liquids in flasks. In addition, a 12-foot-deep concrete bunker, lined with asphalt, is used for containment of medium-level solid wastes. Two double-walled, stainless-steel tanks, each with a capacity of 120 US gallons, were set in concrete, poured into an excavation in the drift some 19 ft. below ground level, and assigned to storage of high-level liquids.

4.6 Underground Waste Management in Adjacent Areas

It is noteworthy that within the Williston Basin region as a whole, deep-well injection of fluid, industrial wastes is largely restricted to the broad, relatively shallow, tectonic shelf, which is the Canadian portion of the area (Simpson and Dennison, 1975). In North Dakota, where the basin fill attains a maximum thickness in excess of 16,700 feet, fluid injection appears to be for the most part confined to the salt-water-disposal and pressure-maintenance operations of the oilfield districts, although the caption of a figure, provided by Arndt (1972, Fig. 10, p. 9) is an explicit statement of contamination of a water supply by injected sewage from an unspecified "small town in western North Dakota." Oilfield-brine injection accounts for all fluid disposal down wells in neighbouring South Dakota and Montana.

In Saskatchewan, however, deep-well injection of fluid, industrial wastes, exclusive of oilfield operations, has been employed as a viable mode of disposal since 1958 (Simpson and Dennison, 1975). At this time, some 32 waste-injection operations have been initiated in the area to receive large quantities of "natural" brines, produced as a result of commercial solution of evaporite minerals, and comparatively minor volumes of "foreign" fluids, generated by 2 refineries and 1 chloralkali plant. Brines, generated by 7 companies in the processing and mining of potash are from the Middle Devonian Prairie Evaporite, are injected in 13 disposal systems. Reservoir strata at depths in the range 1,448 to 4,692 ft. receive potash-mine brines at injection rates of 175 to 1,100 U.S. g/m and pressures of 180-910 psig. Brines are also produced through the controlled solution of evaporite strata to create artificial caverns for the underground storage of liquefied petroleum gases and are injected down 11 wells into aquifers 1,600 to 3,571 feet below K.B. at rates of

200 to 350 U.S. g/m and pressures of 0 to 1,750 psig. A Saskatoon chemical plant used a single well to inject herbicide wastes at 20 US g/m and 150 to 400 psig and mercury-contaminated brines at 20 US g/m and 175 to 250 psig at different times into an aquifer 1,860 ft. below K.B; the same chemical plant utilizes 3 salt caverns at depths of 3,358 to 3,409 ft. below K.B. and mercury compounds are permitted to accumulate in these. A salt plant near Unity disposes of waste brines down a well to a depth of 2,816 ft. at 40 U.S. g/m and 700 psig. Refinery wastes are injected at 2 facilities: the respective disposal depths are 2,690 and 3,840 ft.; injection rates, 3 and 22 U.S. g/m; and injection pressures, 0 and 350 psig (Table 7. To date, subsurface

Table 7 - Refinery wastes injected into subsurface strata of the northern Williston basin region

disposal has a good record of safety in Saskatchewan. However, it should be noted that nowhere in the Williston basin region is there to be found a disposal facility, comparable to the Maples injection well, in terms of degree of detail, known about the disposal reservoir, and hazard-free disposal strategy.

The location of the 32 Saskatchewan waste-injection systems, noted above, and 26 facilities in Alberta is shown in Figure 30. All facilities of the entire northern

Fig. 30 - Distribution of deep-well injection systems in the Saskatchewan-Nelson drainage basin.

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 injection systems: 1 - perimeter of Precambrian Shield, 2 - major basin, 3 - sub-basin, 4 - internal drainage, 5 - subsurface disposal system.

Williston basin region are situated in the Saskatchewan-Nelson drainage basin. Clearly failure of disposal systems and contamination of surface waters in Saskatchewan and, to a smaller extent, Alberta could have serious interprovincial consequences, from the standpoint of Manitoba.

4.7 Note on Contamination of Ground Water by Refined Petroleum Products

The Manitoba Clean Environment Commission (1975) reports that contamination of underground water supplies by refined petroleum products has been recorded from 32 communities in the province and that the problem appears to be more acute in Manitoba than in other Canadian provinces. Natural removal of the petroleum products from contaminated aquifers by dispersion and break-down is extremely slow, operating over time periods of the order of decades. The principal sources of contamination are:

(1) leakage of underground storage tanks, which in the absence of cathodic protection and the best protective coating have an average life of up to 12 to 15 years;

(2) accidental spills during storage, handling and transportation, usually a result of human error; and

(3) indiscriminate dumping of waste oil, especially the dumping of waste crankcase oil in ditches.

The Clean Environment Commission (op. cit.) proposed use of sensitivity mapping to delineate areas, most susceptible to ground-water contamination by leaking storage tanks, by means of criteria such as corrosive properties of soils, permeability of strata and aquifer use, especially with regard to exploitation for domestic water supply.

5. SUBSURFACE-DISPOSAL POTENTIAL

5.1 General Statement

The search phase of subsurface-disposal strategy is ideally directed toward location of definite drilling targets, which are configurations of strata with improved reservoir quality, similar to the stratigraphic and structural-stratigraphic trap geometries, sought as hydrocarbon prospects (Dennison and Simpson, 1973; Simpson and Dennison, 1975). Obviously, the drilling targets for deep-well disposal should not contain commercial accumulations of formation fluids, such as crude oil, natural gas, helium and brines with economic quantities of dissolved solids. Therefore many of the drilled structural-stratigraphic figurations of strata, designated "goelogic successes" but "economic failures" in oil exploration (Hardin and Mygdal, 1968) are prime waste-disposal prospects. The oil and gas pools of the northern Williston basin region reflect dominance of the stratigraphic trap in the area (Davies et al., 1962; McCabe, 1963, 1971; Christopher et al., 1971, 1973).

5.2 Use of Formation Waters

As noted above, existing and potential uses of formation waters exert an important constraint upon exploitation of deep aquifers for waste disposal. Currently there are 2 prinicipal approaches to ground-water use in Manitoba:

(1) Aquifers are widely used for domestic, municipal and industrial water-supply purposes. A noteworthy example is provided by the Palaeozoic Carbonate Aquifer in the metropolitan Winnipeg district; which yielded up to nearly 20 cfs on a continuing basis through a well field, supplying the city from 1900 to 1919 (Render, 1970;

Saskatchewan-Nelson Basin Board, 1972). The aquifer still supplies water for industrial, municipal and air-conditioning purposes in metropolitan Winnipeg at a total estimated annual pumpage of 1.2×10^4 acre-feet (Render, op. cit.). Significant quantities of water, in the order of 0.1 acre-feet per year, are also obtained from the same aquifer at both Selkirk and Gimli (Saskatchewan-Nelson Basin Board, op. cit.). The total discharge rate from the aquifer due to man is about 3.6×10^4 acre-feet per year, which includes discharge into the Red River Floodway, uncontrolled discharge through flowing wells and discharge through thousands of low-capacity wells, in addition to the pumpage, noted above (Saskatchewan-Nelson Basin Board, op. cit.). The Carbonate aquifer is the most extensive in southern Manitoba, but also used for water-supply purposes are Mesozoic sandstone and fractured shale aquifer in western Manitoba, the uppermost Cretaceous and Tertiary sandstones of the Turtle Mountain area, and sand-and-gravel aquifers at a wide variety of locations (Appendix II).

(2) Relatively deep formation brines have been exploited for their dissolved solids by companies in southern Manitoba since about 1913 (Table 8). The Canadian

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Table 8 - Exploitation of salts, dissolved in subsurface formation brines of the northern Williston basin region

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Salt Company Limited produced salt from subsurface brines of the Souris River and Winnipegosis Formations, penetrated by 2 wells at Neepawa at depths of 1160 feet and 1,453 feet respectively (Fig. 31). The salt is precipitated by the

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Fig. 31 - Occurrences of commercial brines in Palaeozoic strata at Neepawa, southern Manitoba

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vacuum pan evaporation process and chlorides of calcium, magnesium and potassium are recovered as a by-product (Bannatyne, 1960). Deep formation brines are also withdrawn for commercial purposes by Hooker Chemicals Canada Limited at Brandon; the aquifers yielding brine production belong to the Red River and Winnipeg Formations, penetrated at 3,267 feet and 3,296 feet below surface respectively in one well, and the Winnipegosis Formation at 2,190 feet below surface in a second well. The composition of the Winnipegosis brines (J. D. Ross, pers. comm. to Simpson, 1973) is shown in Table 9. Hooker's process[1] entails

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Table 9 - Composition of brines from the Winnipegosis Formation, utilized by Hooker Chemicals Canada Limited at Brandon, southern Manitoba

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electrolysis of brines to produce sodium chlorate, chlorine, caustic soda, sodium carbonate and muriatic acid.

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[1]Once-through cooling water, used at the plant, is withdrawn from a shallow, on-site aquifer and disposal of the spent cooling water is by dispersal in the nearby Assiniboine River

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(3) Potential uses of formation waters are the production of calcium and magnesium from the brines of deep aquifers, proposed for southern Alberta by Hitchon and Holter (1971), and the extraction of scarce halogens, such as bronine and iodine, also from deep brines.

5.3 Hydrocarbon Potential

The most recent studies of the gydrocarbon potential of the northern Williston basin region are those by Christopher et al. (1971, 1973), whose views on the eastern part of the area form the basis for the following remarks. The parts of the Phanerozoic sequence, regarded as particularly favourable for petroleum exploration in Manitoba are:

(1) The Winnipeg Formation (Middle Ordovician), where favourable reservoir characteristics in relatively coarse-grained deposits are obtained on the flanks of positive relief features of the Precambrian surface;

(2) Ordovician carbonates particularly those of the Red River Formation, along the edge of the Prairie Evaporite;

(3) Reef carbonates and calcareous sands of the Lower and Middle Interlake (Silurian), particularly at the subcrop, where dolomitic mudstones are interbedded;

(4) The Middle Devonian Winnipegosis shelf carbonate facies, peripheral to the Elk Point basin, and coquinoidal and pisolitic strata, flanking carbonate mounds;

(5) Dawson Bay (Middle Devonian) and Souris River (middle Upper Devonian) carbonates along the eastern margin of the Prairie Evaporite basin;

(6) Duperow (Upper Devonian) dolomites at locales, peripheral to evaporite accumulations and passing laterally into low-permeability carbonates;

(7) Birdbear (Upper Devonian) carbonates, associated with multistage salt-solution structures;

(8) The Bakken Formation (Mississippian), where secondary porosity and permeability occur along fracture zones, related to multistage salt-solution features and basement-controlled flexures;

(9) The westward extension of the near-shore Lodgepole facies, productive in the Virden district;

(10) Extensions of present Mississippian production to infill- and outpost-drilling location, where there is (a) updip passage from dolomites and dolomitized limestones to less permeable, non-dolomitized lime-mudstones in reservoir configurations of strike-parallel permeability change and structural relief; and (b) updip loss of porosity

through anhydritization and dolomitization in carbonates, truncated at the sub-Mesozoic unconformity, with reservoir configurations determined by strike-parallel decrease in permeability, which is in turn controlled by facies variation and a combination of structure and palaeotopography.

5.4 Possible Environmental Impact of Subsurface Disposal

Possible effects of deep-well disposal of fluid, industrial wastes, considered below, relate principally to the danger of contamination of surface and near-surface waters, as a result of failure to confine the plume of injected substances to the disposal aquifer. The same effects obviously may arise as a consequence of faults, developed in a disposal well itself during a period of operation, but aspects of well design are not discussed here.

In southern Manitoba, constraints on the choice of both disposal site and receiving aquifer are imposed by hydrogeologic factors, which could exert a profound influence on patterns of subsurface migration of wastes:

(1) Disposal sites should be situated at points distant from the outcrop belt of central and eastern parts of the province, so as to minimize the hazard of waste substances being discharged together with formation waters in this area. Deep waste injection is likely to be safer than shallow waste injection, principally because

the deeper aquifers are separated from surface and near-surface supplies of fresh water by a greater aggregate thickness of barriers to vertical fluid migration than are the relatively shallow ones. Therefore, new waste-injection facilities should be restricted to the thicker parts of the Phanerozoic succession, occurring in the southwestern corner of the province.

(2) Valley systems, incised at the karstic sub-Mesozoic surface in Mississippian and Devonian rocks, have controlled structure and isopach configurations in the Mesozoic and Cenozoic deposits of the northern Great Plains region. Most importantly, these antecident valley configurations coincide spatially with and apparently have exerted strong control on patterns of fluvial valley systems of Early Cretaceous, Late Cretaceous - Tertiary, Pleistocene and Holocene ages. These largely parallel valley systems impart a considerable anisotropy of flow of formation waters and care should be taken to avoid them, when sites are selected for deep-well injection of wastes.

(3) Fracture-bounded sinks are fairly common features in strata, younger than Middle Devonian, throughout much of the northern Great Plains region. These structures have resulted from localized solution of Middle Devonian evaporite beds and related collapse of superjacent strata. In distribution, many of these sinks are also closely related to palaeotopographic expression of valley systems

at the sub-Mesozoic unconformity. Waste-injection sites should be located in areas where salt-solution sinks are absent, since these features might constitute conduits for the upward migration of wastes under pressure, thus promoting cross-formational flow and possibly flow to surface.

(4) Positive relief features at the Precambrian surface and overlying structures in the Phanerozoic succession should be avoided, when disposal sites are selected. Palaeotopographic highs would bave the effect of deflecting the injection-augmented flow of formation waters and wastes upwards and would thus tend to promote cross-formational flow. Furthermore, the basement features, thought to be of crypto-explosion origin, are bounded by fractures, which could be reactivated by high injection pressures. Also the probable cansative relationship between positive basement relief and features, related to collapse following localized evaporite solution, should be taken into account.

(5) The area around a proposed waste-injection site should be checked carefully for the possible existence of a small number of improperly abandoned, oil-exploration wells, dating back to the early years of drilling, especially in the western part of the province. These wells were mostly drilled to shallow Cretaceous targets near the Saskatchewan border, though deeper strata may

be penetrated in some cases. Clearly such well bores would provide wastes under pressure with paths of easy movement to the surface and proper abandonment procedure should be instituted before initiation of waste-injection operations.

5.5 Subsurface Space Categories

In their study of the subsurface-disposal potential of Saskatchewan, Simpson and Dennison (1975, Table 20, page 67) presented a speculative table, relating 7 main categories of subsurface space to types of waste, which might be confined or contained in them, and assigning a "recommended waste-management status" to each category. Table 10 is essentially revised version of this earlier

Table 10 - Waste-disposal potential of different types of subsurface space in Manitoba

table, modified in format for the specific geologic setting of Manitoba.

5.6 Waste Types

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

(1) Industrial operations generating foreign wastes are concentrated to a large extent in the Winnipeg district, where neither surface disposal nor deep-well injection of such substances is feasible, because of the risk of contaminating municipal and industrial water supplies. Therefore deep-well disposal can only be seriously considered as an option at sites distant from the waste-generating process. Since off-site disposal is likely to be of increasing importance in the future, the experience of waste injection at the Maples disposal site, summarized by Simpson *et al*. (in press), is expected to assume considerable practical value for intending disposal-well operators.

(2) The economic potential of the Middle Devonian Prairie Evaporite in the Lazare district of southwestern Manitoba is thought to be good (Bannatyne, 1960, 1971). The main potash-bearing unit of the Prairie Evaporite in Manitoba is 6 to 8 feet thick and contains 25 per cent K_2O. The unit occurs at depths as shallow as 2,560 feet below surface and is succeeded by 60 to 85 feet of halite. The unit has not been exploited commercially as yet, either for production of potash or mining of common salt. A

further possible means of exploiting the Prairie Evaporite might be through artificial solution of halite beds to create caverns for the underground storage of liquefied petroleum gases. In each instance, waste brines would be generated. Surface impoundment of such brines in surface lagoons and ponds renders arable farmland useless and, as noted by Vonhof (in press), presents the danger of contamination of both surface waters and near-surface aquifers. For these reasons, potash-mine operatirs in Saskatchewan have come to adopt deep-well injection as a mode of disposal for their waste brines and the same hydrogeologic factors, which control waste injection by these operators, are likely to be valid in Manitoba. In Saskatchewan, potash-brine injection is on-site at high pressures (up to 900 psig) and high rates (up to 1,100 U.S. g/m); disposal is into stratigraphic units, located below the Prairie Evaporite, so as to minimize the hazard of mine flooding (Simpson and Dennison, 1975). The disposal aquifers, utilized by Sylvite of Canada Limited and International Minerals and Chemical Corporation (Canada) Limited who operate potash mines west of the Saskatchewan, are the biohermal deposits of the Silurian Interlake Group and siliciclastic rocks of the Middle Ordovician Winnipeg Formation. These same units might be exploited for emplacement of waste potash brines in Manitoba.

5.7 Alternative Modes of Disposal

Dennison and Simpson (1973) reported that an alternative surface method of disposal would cost at least 2 to 3 times the total ultimate capital investment in each subsurface-disposal facility at that time in operation in the northern Williston basin region. In Manitoba, many industrial operators, based in the southeast, who may in future consider deep-well injection as a waste-disposal option, must take into account the increased costs, relating to transportation of the wastes to the safest, potential disposal sites, located in the southwest. In the event of the potash industry at last coming into its own in southern Manitoba, mine operators will no doubt benefit from the experience of Saskatchewan-based companies with regard to waste disposal and in particular disposal of waste brines. The only alternative to deep-well injection of potash brines is containment in surface lagoons, rendering large areas of farmland unfit for use and, as noted by Meneley (1965) and Vonhof (1971), tends to endanger surface and near-surface waters, which might be of future, commercial importance. Canadian Salt Company's commercial exploitation of potash brines, generated by Kalium Chemicals Limited at Belle Plaine, Saskatchewan, described by Simpson and Dennison (1975), is an outstanding example of reduction of wastes through co-operation between companies and the feasibility of a similar arrangement might be considered in future, should potash production begin in Manitoba.

6. RECOMMENDATIONS

Industry has an extremely good record of safety in subsurface disposal of wastes in Manitoba. Experience in handling contrasting waste categories in a variety of subsurface settings since the early 1950's suggests that this general approach to waste management is viable in the hydrogeologic milieu of southwestern Manitoba.

Biohermal deposits and unconformity-related stratigraphic traps in beds ranging in age from Middle Ordovician to Middle Silurian could be considered in future for waste injection or, alternatively, for aquifer storage of natural gas or even fresh water for municipay or industrial use in the Manitoba onshore part of the Hudson Bay basin region. Of course, the need for such facilities in this remote northern area is not yet foreseen, but clearly any future feasibility study, related to any specific disposal or storage situation, must take into account the unique and poorly understood ground-water regime of a permafrost region, since water supply must assume a priority, higher than that assigned to waste disposal.

In southern Manitoba, on the other hand, the considerable diversity of industrial development, particularly in the Winnipeg district, and the presence particularly in the Winnipeg district, and the presence of several deep aquifers with subsurface-disposal potential ensure immediate interest in deep-well disposal as a possible waste-disposal option. Because of the risk of contamination of potable water in the urban centres, where most waste-generating industrial processes are located, off-site waste injection will be the only feasible means of initiating subsurface disposal. This need for off-site location of disposal facilities in turn presents the highly desirable possibility of greatly increased range of choice of disposal aquifers. The present survey has led to the formulation of several recommendations, which might usefully serve as guidelines for intending disposal-well operators:

(1) Waste injection should be restricted to the deepest aquifers with good reservoir quality at locations, distant from the outcrop belt, and to the shallower reservoir units of the oilfield district. According to this line of reasoning, aquifers with the greatest potential for receiving fluid, industrial wastes are sandstones of the Ordovician Winnipeg Formation and biostromal carbonates of the Silurian Interlake Group at sites, restricted to the southwestern corner of the province, and Mississippian carbonate strata (Lodgepole and Mission Canyon Formations), where the latter are truncated at the sub-Mesozoic unconformity in watered-out oil-production locales.

(2) Mesozoic and Cenozoic strata should be rigorously

excluded from all considerations of possible options for disposal aquifers. These shallow units are largely unsuitable for waste injection, because of the close spatial coincidence between modern fluvial valley systems and ancient, antecedent systems, which is controlled to a large extent by salt-solution phenomena. In these deposits, fracture-bounded sinks, formed through localized solution fo Middle Devonian evaporite beds, may constitute conduits for easy upward movement of waste fluids under pressure. Waste injection in close proximity to such features also presents the possibility of injection-induced crustal instability as a result of lubrication of fracture zones.

(3) Waste injection into deep disposal aquifers should be conducted at locales distant from positive relief features at the Precambrian surface. This strategy would minimize the danger of cross-formational flow, due to upward deflection of the waste plume over basement highs. As noted in Section 3.2 above, some positive basement features are bounded by fractures and movement might be induced along these by the lubricating action of injected wastes under high pressure.

(4) There is a threat of pollution of surface and near-surface waters by injected wastes, where subsurface disposal is effected in the vicinity of open well bores, which provide a means of easy, upward escape of fluids

under pressure, There may be a relatively small number of improperly abandoned wells of uncertain location, which were drilled to shallow Mesozoic targets in the western part of the province during the early years of oil exploration. All such wells in the immediate vicinity of any proposed disposal site should be located and abandoned by the disposal-well operator, as is the case in southwestern Ontario.

(5) In the event of deep-well disposal of wastes becoming extensively practiced in southwestern Manitoba, considerable attention should be paid by the public and private sectors of decision-making to implementation of all approaches to the monitoring of disposal operations, listed in the Introduction. In addition, consideratio- should be given to the possible gains to be derived from monitoring formation-water composition by means of a series of deep observation wells, which might be drilled along a line, parallel to the outcrop belt.

Manitoba has the opportunity to utilize a number of categories of subsurface space, about which relatively little is known from the standpoint of hydrogeology. These space categories are listed in Table , where the need for further research is noted:

(1) The shales of the Winnipeg Formation may be rendered suitable for use as repositories for industrial wastes by hydraulic fracturing, followed by introduction

of cement and minor quantities of fluid wastes. The theory of hydraulic fracturing and grouting as a mode of disposal for noxious wastes is discussed by Sun (1973). Only the thickest sections of Winnipeg shales could be considered for this type of subsurface-disposll activity. Locales with a high occurrence of thin sandstone and coarse siltstone intercalations in vertical succession would present a danger of lateral migration of wastes and should be avoided.

(2) Artificial subsurface space in evaporite strata provides interesting possibilities for use in waste containment and is being exploited increasingly for the storage of radioactive wastes in many parts of the world. The space provided by mine workings of room-and-pillar type in evaporites, currently is restricted to Jurassic anhydrite-gypsum beds at shallow depths and many have some future application in underground waste management. At the present time, the Middle Devonian Prairie Evaporite is without artificial space of this type, but the possibility of disposing of minor amounts of wastes into artificial solution caverns merits careful consideration for the future. Feasibility studies relating to this mode of disposal should pay particular attention to minor, though significant porosity-permeability gradients in evaporite strate, which

Aufricht and Howard (1961) consider to be related to:

(a) the type and amount of impurity in halite, including shale and mudstone layers;

(b) the crystalline structure of the halite and orientation of cleavage plumes;

(c) the confining or overburden pressure on the evaporite sequence; and

(d) the water content.

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

(3) The hydrogeology of the Precambrian Shield merits detailed study and is poorly known at the present. Sealed containers of toxic wastes might be stored in shallow,lined excavations in basement rocks, distant from major fault zones and in the absence of closely spaced joints.

7. CONCLUDING REMARKS

1. Rocks with good reservoir quality and potential for receiving fluid, industrial wastes occupy 2 main areas in Manitoba:

(a) the southern part of the Hudson Bay basin region in northeastern Manitoba (26,000 square miles), where over 2,900 feet of Ordovician, Silurian and Devonian strata occur below the surface onshore; and

(b) the northwestern part of the Williston basin region in southern Manitoba (76,000 square miles), where beds, ranging in age from Ordovician to Tertiary, attain a maximum thickness of about 8,000 feet in the extreme southwest.

The hydrogeology of a third important area, the Manitoba segment of the Precambrian Shield (149,000 square miles), is poorly known and this region cannot be considered for subsurface waste disposal.

2. The southwestern Hudson Bay basin region has an onshore stratigraphic succession, which comprises 2 main sequences of limestone, dolomites and minor evaporties, Middle Ordovician to Middle Silurian and Lower to Middle Devonian in age respectively, separated by Upper Silurian through Lower Devonian dolomites, fine-grained red beds and subordinate evaporites. The northeastern Williston

basin region has a stratigraphic succession, characterized by greater lithologic variation:

(a) a lower clastic division, consisting of sandstones and shales, belonging to the Middle Ordovician Winnipeg Formation, which reaches a maximum thickness of about 350 feet;

(b) a carbonate-evaporite division, Middle Ordovician through Mississippian in age, which includes up to 500 feet of potash-bearing (Middle Devonian Prairie Evaporite) and has a maximum thickness of about 4,000 feet; and

(c) an upper clastic division, Triassic (?)-Jurassic through Recent in age, which incorporates 25 to 175 feet of anhydrite with minor shale and dolomite near the base and reaches a maximum thickness of about 3,500 feet.

3. At present, 4 main types of fluid waste have undergone disposal into subsurface strata in southern Manitoba:

(a) Brines withdrawn during commercial production of crude oil have been injected back into Mississippian oil-reservoir strata at depths of 2,010 to 3,270 feet below surface in both pressure-maintenance and salt-water-disposal wells of the oilfields in the southwest.

(b) Spent caustic wastes from the Imperial Oil Enterprises Limited refinery in Winnipeg were injected at o psig and 3.5 U.S. g/m into carbonate reservoir strata of the Lodgepole Formation (Mississippian) at 2,080 feet in a reworked producing well at a down-dip location in the Maples oilfield from 1969 to 1975.

(c) Spent cooling water from air-conditioning systems in theatres and restuarants and from cold-storage plants in central Winnipeg is injected back into the same Palaeozoic carbonate aquifer, which has served these facilities since 1919.

(d) Low-, medium-and high-level, solid, radioactive wastes and subordinate amounts of liquid, radioactive wastes from the Whiteshell Nuclear Research Establishment of Atomic Energy of Canada Limited have been stored since 1964 at depths of up to 15 feet in Pleistocene clay and till, resting on glacial sands, above Precambrian bedrock near the plant.

Subsurface disposal of wastes in southern Manitoba is remarkable, as compared with that of other Canadian provinces, in that it is carried out in areas of extremely good well control, reflecting development drilling in the oil-production and ground-water-withdrawal locales and test drilling at Whiteshell. Thus many of the uncertainties, inherent to the underground-waste-management decision system and in particular those relating to reservoir geometry of the disposal formation and flow pattern of formation fluids, are largely eliminated.

4. In the Manitoba onshore part of the Hudson Bay basin region, biohermal deposits and unconformity-related

stratigraphic traps in beds, ranging in age from Middle Ordovician to Middle Silurian, could be considered in future for waste injection or, alternatively, for aquifer storage of natural gas or even fresh water prior to municipal or industrial use. The need for such facilities in this remote area is not yet foreseen. In southern Manitoba, on the other hand, continuing interest in deep-well injection as a possible waste-disposal option is ensured by growth of a diversified industrial economy in the southeast and the occurrence of commercial, though as yet unexploited potash and halite deposits in the southwest. Sandstones of the Ordovician Winnipeg Formation and biostromal biostromal carbonates of the Silurian Interlake Group are used as disposal aquifers by the potash industry in Saskatchewan and are the aquifers with greatest potential for receiving industrial wastes in southwestern Manitoba. Waste injection into oil-reservoir strata of the production districts by means of reworked oil wells is worthy of close consideration, because of the detailed subsurface information, available at these locales.

5. The Mesozoic and Cenozoic successions of southwestern southwestern Manitoba should be strictly excluded from all considerations of possible disposal strata by intending injection-well operators. This is in part because of the high degree of spatial coincidence between fluvial valley systems at the sub-Mesozoic unconformity and all later

valley configurations, including those of the present day. The sub-Mesozoic drainage patterns have thus imparted a marked anisotropy of present-day flow to the ground-water regime of younger continental deposits, in that flow is controlled by the orientation of depositional systems. This relationship between modern and antecedent drainage systems was in part controlled by the ditribution and orientation of fracture-bounded sinks at surfaces in the post-Prairie succession, which in turn resulted from collapse of strata, following localized solution of the Middle Devonian evaporite unit. Fractures of salt-solution origin may constitute conduits for easy upward movement of waste fluids under pressure. Salt-solution features may result from impingement of ground-wster flow patterns on the lower surface of the Prairie Evaporite, after upward deflection of the flow by reactivated basement elevations, which may themselves by bounded by fractures. Therefore wsste injection into the basal clastic division should be conducted at locations, distant from palaeotopographic elevations at the Precambrian surface.

6. The possible existence of a small number of improperly abandoned, old oil-exploration of uncertain location poses a threat of pollution for surface and near-surface waters of commercial value. These wells are generally no more than a few hundred feet deep and were drilled to shallow Mesozoic targets in the western part

of the province. Without institution of correct abandonment procedure, these wells would constitute foci for easy, upward movement of wastes under pressure. A reasonable solution to this potential problem might be for the province to assign to prospective disposal-well operators the responsibility for abandonment of all old wells within a predetermined radius from the disposal site.

7. Extreme care must be taken to avoid contamination of commercially important formation fluids, such as crude oil in proven Mississippian and prospective, notably Devonian and Silurian reservoir settings; brines with economic quantities of dissolved solids in the Winnipeg and Winnipegosis Formations; and potable ground water in bedrock aquifers, for example, that of the Ordovician and Silurian carbonate aquifers, which is a source of water supply for metropolitan Winnipeg.

8. Research is needed to determine the suitability of several different types of subsurface space to serve as repositories for industrial wastes, especially for wastes, requiring containment for long periods of time or even forever:

(a) Shales of the Winnipeg Formation may be suitable for hydraulic fracturing, followed by cement grouting and introduction of minor quantities of wastes. Frequency of occurrence of sandstone and siltstone intercalations in the thicker Winnipeg shale sections is a factor of critical importance in controlling the distribution of permeability in the succession. Widespread occurrence of such intercalations could preclude the commercial application of this approach to waste management in southern Manitoba.

(b) Artificially formed, subsurface space in the evaporite strate of Manitoba might be utilized for waste containment in the future. The space, provided by mine workings of room-and-pillar type in evaporites, is presently restricted to Jurassic anhydrite-gypsum beds at shallow depths and may have some future application in underground waste management. The Middle Devonian Prairie Evaporite is without subsurface space of this type at present, but the possibility of disposing of small amounts of wastes into artificial solution caverns merits consideration for the future. Feasibility studies should take into account the minor, though significant porosity-permeability gradients of evaporite strata generally and the migration of microscopic bubbles in halite, both to and from heat sources.

(c) Little is known about the hydrogeology of the Precambrian rocks of the area. This topic deserves detailed study, in that sealed containers with toxic wastes might be stored in shallow excavations in basement rocks, distant from major faults and in the absence of closely spaced joints.

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SUBSURFACE DISPOSAL OF WASTES IN MANITOBA

II - SUBSURFACE DISPOSAL OF REFINERY SPENT CAUSTIC IN THE IMPERIAL VIRDEN 7-8M-10-26 WELL (LSD 7-8-10-26W1): A CASE HISTORY

by

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ABSTRACT

Spent caustic waste from the Imperial Oil Enterprises Limited refinery in Winnipeg was transported by road a distance of about 175 miles to the Imperial Virden 7-8M-10-26 well (Lsd 7-8-10-26 W1), where it was injected into carbonates of the Mississippian Lodgepole Formation from 2,080 to 2,142 feet below kelly bushing. The waste was rich in phenols relative to sulphides and was produced during neutralization and extraction of acidic contaminants in crude oil and the products of treatment reactions and cracking operations. Organic compounds, including phenols, made up 12 to 25 per cent of the injected waste by weight, sulphides and mercaptan sulphur 3 to 7 per cent, caustic soda 5 to 10 per cent, and water 58 to 77 per cent.

The disposal well was originally drilled in July, 1955, as an oil producer in the Maples field of southwestern Manitoba, with 10-3/4-inch surface casing to 513 feet K.B., 7-inch production casing to 2,080 feet K.B. and a 6-1/4-inch open-hole completion to 2,142 feet K.B. The total cumulative production from the well to October, 1969, when it was suspended as a producer, was 21,339 barrels of crude oil (33° API) and 478,370 barrels of water. For waste injection, a well design based on that of oilfield brine-injection systems was favoured, with installation of plastic-lined, 2½-inch tubing, landed at 2,059 feet K.B. and a tension

packer. The annular space between the 7-inch casing and $2\frac{1}{2}$-inch tubing was filled with inhibited fresh water. The rate of waste injection was up to 3.5 US gpm at gravity feed. Approximately xx,xxx barrels of spent caustic waste had been injected through the well to October, 1975 when the refinery was shut down and disposal terminated.

The Maples field obtains crude-oil production from a structural-stratigraphic trap, defined by spatial coincidence of 2 main zones of Lodgepole carbonates with good reservoir quality and one of a series of positive structural features, related to differential collapse, attendant upon localized solution of Middle Devonian evaporite beds. The reservoir strata, which received the refinery wastes, belong to the upper part of the Lodgepole Formation and consist of about 37 feet of dominantly argillaceous, bioclastic limestone with intercalated chert layers and minor anhydrite forming nodules, thin layers and fracture infillings. Coarse, vuggy porosity with individual vugs up to 2 inches in diameter is largely confined to layers in the basal 17 feet of reservoir strata. The limestones are succeeded by argillaceous, sporadically fossiliferous, bioclastic dolomites with generally poor, fine porosity and subordinate, interbedded anhydrite and chert, which in turn are unconformably overlain by fine-grained Jurassic red beds. Containment of the spent caustic waste by Lodgepole strata in isolation from commercial oil accumulations in the same reservoir is controlled by:

(1) dolomitization and anhydritization in the cap rocks;

(2) westward decrease in grain size, porosity and permeability of the reservoir strata;

(3) down-dip penetration of the upper part of the Lodgepole Formation by the disposal well with respect to existing oil production in the Maples field; and

(4) the low injection rates and injection pressures of the disposal system.

Precipitates were formed when various spent caustic solutions were mixed with equal volumes of brine from the Lodgepole Formation in pre-injection laboratory tests. That acidization would be effective in restoring porosity, lost as a result of brine-waste incompatibility in the subsurface environment, was suggested by the fact that between 77.9 and 100.0 per cent by weight of individual precipitate samples were found to be soluble in dilute hydrochloric acid. The possibility of precipitate formation in the immediate vicinity of the open-hole completion was minimized at the beginning of disposal operations through initial injection of 1,000 barrels of fresh water as a buffer pad. In July, 1970 porosity was restored after plugging, by means of acidization with 250 gallons of 28 per cent hydrochloric acid, injected at 3 barrels per minute and 600 psig.

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1. INTRODUCTION

1.1 General Statement

The Maples oilfield is located in southwestern Manitoba, 2 miles along Manitoba Rte. 83, south of the intersection with the Trans-Canada Highway, and some 175 miles west of Winnipeg (Fig. 1). Production of high-gravity crude oil

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Fig. 1 - Location map showing the Maples oilfield and the Imperial Virden 7-8M-10-26 well (Lsd 7-8-10-26 Wl) in the oil production district of southwestern Manitoba.

(33° API) has been obtained from carbonates of the Mississippian Lodgepole Formation at the Maples field since completion of the discovery well, Imperial Virden 5-9-10-26 (Lsd 5-9-10-26 Wl) in February, 1955. The field occupies a developed producing area of approximately 520 acres and incorporates 7 wells, capable of producing, 5 of which actually produce, drilled on 40-acre spacing. The average depth of the pay is 2,105 feet below surface. Production is from 2 Lodgepole zones (Fig. 2), which give an average

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Fig. 2 - Stratigraphic correlation chart showing Mississippian formations, which yield production of crude oil in the northern Williston basin region.

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aggregate thickness of 45 feet, the maximum value for average pay thickness in the Manitoba oil-production district. The Maples field ranks sixth among the 15 principal production locales of southwestern Manitoba in terms of original oil in place, estimated at 10,456,000 bbls, of which 724,000 bbls are reserves, recoverable by primary means. The total cumulative production of oil at Maples to December 31, 1974, was 700,515 bbls, with water drive the natural depletion mechanism. The water saturation of the Maples reservoir is 40 per cent and the cumulative water production to December 31, 1974, was 9,542,256 bbls.

In April, 1969 Imperial Oil Limited applied for a permit to dispose of spent caustic solutions from the company's Winnipeg refinery into the upper part of the Lodgepole Formation of the Maples oilfield. The company proposed to inject the wastes down the Imperial Virden 7-8M-10-26 well (Lsd 7-8-10-26 W1), a suspended oil producer, which penetrates the Lodgepole Formation at a down-dip location within the Maples field. In September, 1969, the Oil and Natural Gas Conservation Board of the Manitoba Department of Mines and Natural Resources granted the company Refinery Waste Disposal Permit No. 1, subject to the provisions of the Mines Act R.S.M. 1954 and amendments to the Act, with the additional conditions:

(1) that the maximum wellhead pressure of waste injection should not exceed 1,000 psig at any time;

(2) that volumes of injected waste and maximum injection pressures be reported to the Mines Branch each month; and

(3) that the Conservation Board reserves the right to alter or rescind permission for disposal at any time without notice.

The well was converted to a refinery-waste disposal well on October 27, 1969, and 2 days later went on stream.

It is noteworthy that in late 1971, Imperial Oil Limited announced plans to begin construction of the 140,000 bbls/day Strathcona refinery at Edmonton. Completion of the new refinery was to be accompanied by the closing down of then existing facilities at Calgary, Edmonton, Regina and Winnipeg. Thus, after only 2 years of subsurface disposal at the Maples site, it became clear that injection of refinery spent caustic would continue for no more than 4 further years. Waste injection ceased and the disposal well was suspended, when Imperial Oil's Winnipeg refinery operations were terminated in October, 1975.

1.2 The Problem

The refinery of Imperial Oil Enterprises Limited was a skimming, cracking and asphalt facility, receiving crude oil from Alberta, Saskatchewan and Manitoba fields. The plant went on stream in 1951 and maintained a throughput of about 22,500 bbls per day, before being shut down in the fall of 1975 as part of Imperial Oil's plans to centralize refinery operations in Edmonton. The chief products made for sale were motor gasoline, aviation gasoline, tractor fuel, aviation turbine fuel, kerosene, stove oil, diesel fuel, light and heavy fuel oils, asphalt and sulphur. The main waste-treatment facilities in use at the plant were:

(1) an API oil-water separator to separate free oil from the refinery waste ("clean" and oily) waters;

(2) stabilization ponds with aeration to reduce the oxygen demand, toxicity, oil content, taste and odour of refinery effluent; and

(3) a sour-water stripper for removal of relatively volatile compounds, such as hydrogen sulphide and ammonia, from foul refinery waters.

These processes rendered the greater part of the refinery effluent suitable for disposal into the municipal sewerage system. Caustic solutions were used for neutralization and extraction of various acidic compounds, both naturally occurring in crude oils and produced in refinery processes, and deep-well injection was selected as a means of isolating the resulting spent caustic from potable water supplies.

The Winnipeg site of the Imperial Oil Limited refinery is unsuitable for subsurface disposal. Metropolitan Winnipeg is underlain by 30 to 200 feet of Quaternary deposits, resting on a karstic bedrock surface, dissected into Ordovician carbonates formations in order of increasing age, which (Stonewall, Stony Mountain and Red River) locally range in thickness from 250 to 750 feet. Beneath the carbonate sequence, up to 130 feet of sandstones and shales, belonging to the Ordovician Winnipeg Formation, rest upon Precambrian basement rocks. The carbonate succession incorporates 2 aquifers: a major, partially confined aquifer (Upper Carbonate aquifer) in the top 50 to 100 feet of the sequence and a minor aquifer (Lower Carbonate aquifer) in the basal 25 to 50 feet (Render, 1970, 1971). The Upper Carbonate aquifer is a ground-water transmission zone, which yields about 17 per cent (3 billion gallons) of the annual water supply of metropolitan Winnipeg and is growing in importance as a commercial water source (Render, 1970). Hydraulic continuity between (1) the carbonate aquifers and the ground surface and (2) the carbonate succession and sandstone aquifers of the underlying Winnipeg Formation is obtained, where artesian rise of waters is related to major excavations and open well bores respectively (Render, 1970). Clearly the hydrogeologic setting of metropolitan Winnipeg and the extensive use of ground water for domestic and industrial purposes preclude the use of subsurface space for containment of fluid wastes: only the basal Ordovician sandstone aquifers might be seriously considered for waste injection, but the high risk of upward migration of noxious fluids along open well bores eliminates these units as potential disposal intervals. It was therefore necessary to examine possibilities of deep-well disposal at a site distant from the refinery and the suspended Imperial Virden 7-8M-10-26 oil well (Lsd 7-8-10-26 W1), owned by the company, was a logical choice.

1.3 Waste-Injection Decision System

A decision to inject fluid wastes into subsurface strata is usually made under considerable uncertainty, in that subsurface-disposal operations are for the most part initiated at locales, where few wells have been drilled to penetrate the disposal formation (Dennison and Simpson, 1973). Consequently, well control with regard to the disposal interval is generally poor and information on lithology and fluid-flow characteristics of the unit frequently comes from (1) the disposal well itself and (2) distant stratigraphic-test holes and petroleum exploration wells, distributed over a wide area around the disposal site. An important exception is provided by subsurface-disposal operations, in which wastes are injected into the hydrocarbon-depleted pay strata of an oil or gas field. Clearly such locales are generally characterized by good well control for the pay zone and detailed understanding of three-dimensional variation in reservoir quality. In the Maples oilfield, the reworked producing well, which was used for disposal of refinery wastes, is among 17 wells penetrating the Lodgepole pay strata. Indeed, when disposal operations were initiated, a total of 8 wells was drilled on section 8-10-26 W1.

As noted by Simpson (1975), the prime objective of subsurface disposal is isolation of wastes from the biosphere and principal sub-objectives may be recognized through reference to a generalized systems model of a waste-injection facility (Fig. 3), which consists of 3 subsystems:

Fig. 3 - General systems description of a waste-injection facility.

(1) an actuator, the disposal well, through which matter (fluid, industrial wastes) and energy (injection pressure and heat of exothermic chemical reactions) are directed into subsurface reservoirs;

(2) injection-affected subsurface space of the disposal interval, in which the growing plume of wastes is accommodated in the vicinity of the disposal well bore by displacement of formation fluids and structural adjustment of the reservoir framework; and

(3) a transducer or monitoring device, providing a continuous record of both waste behaviour in the subsurface environment and response of reservoir strata to injection, in addition to presenting a means of determining efficiency of the disposal well itself.

Injected wastes are ideally confined to the well bore and the receiving strata in the immediate vicinity of the well bore; minimal checks on well preformance and waste subsurface interaction are obtained through monitoring of injection pressure or injection rate.

1.4 Scope of Study

This report provides a detailed case history of the well, used by Imperial Oil Enterprises Limited for subsurface disposal of refinery wastes at Maples, and is intended to supplement an earlier, more general account of the feasibility of deep-well injection of wastes in Manitoba (Simpson et al., in press). Both pre-injection withdrawal of formation fluids and injection of liquid wastes are documented and discussed in the light of information on the hydrogeologic setting of the Maples reservoir. The subsurface disposal operation described in the present account is noteworthy for the following reasons:

(1) Waste injection at an oil-production locale affords a rare opportunity to investigate the possible effects of subsurface disposal in an area of good well control.

(2) Injection operations were well documented throughout the entire 6-year disposal history of the facility, which permits a detailed, retrospective integration of design process and well life cycle (Table 1).

Table 1 - The disposal-well life cycle

(3) Low injection rates and pressures, as well as pre-injection withdrawal of formation fluids, in amounts greatly exceeding those of the injected wastes, are part of a subsurface-disposal strategy, which reduces pollution hazard to an absolute minimum.

Data presented and discussed in this account came from non-confidential files of the Manitoba Department of Mines, Resources and Environmental Management and from a questionnaire, completed by Imperial Oil engineering personnel in 1973. The questionnaire consists of 40 questions, aimed at an understanding of the subsurface disposal decision system, and is identical in format to the one, used in a study of Saskatchewan waste-injection facilities by Simpson and Dennison (1975, pp. 73 and 74).

2. THE WASTES

2.1 General Statement

Spent caustic solutions are among a small number of typical wastes, generated by almost all refinery operations and consequently studied extensively with regard to alternative options for handling and disposal. As noted by the American Petroleum Institute's Committee on Disposal of Refinery Wastes (American Petroleum Institute, 1969), however, each refinery has unique waste-management problems, determined largely by design of the refinery processes in use and standards of water quality, imposed by regulatory organizations. Therefore no universal strategy has yet been developed with regard to disposal options for refinery spent caustic.

2.2 Waste Sources

Typical uses of caustic soda in refinery processes (American Petroleum Institute, 1969) are neutralization and extraction of a variety of acidic substances, (1) occurring naturally in crude oil and its fractions, (2) produced in chemical reactions of the refinery treatment processes, and (3) generated during catalytic and thermal cracking operations. These acidic contaminants include hydrogen sulphide, mercaptans, phenols and thiophenols.

2.3 Composition

In a comprehensive survey of the aqueous wastes of refineries and petrochemical plants, Beychok (1967) distinguished between those spent caustic solutions, relatively enriched in phenols, and those with relatively high proportions of sulphides. The sulphidic spent caustics, containing no phenols, are usually amenable to treatment, involving oxidation with air. Solutions, rich in phenols, may be treated with acids for release and removal of the phenols. As shown in Table 2, the aqueous

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Table 2 - Composition of refinery wastes injected into the Lodgepole Formation through the Imperial Virden 7-8M-10-26 well (Lsd 7-8-10-26 W1)

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wastes from the Imperial Oil Enterprises Limited refinery in Winnipeg were rich in phenols relative to sulphides.

2.4 Physical Properties

The spent caustic solutions contained high proportions of water and consequently had physical properties, closely corresponding to those of water. The specific gravity was approximately 1.1 (10 to 25 degrees Baumé). The viscosity was about 1.8 centipoises at 100°F. Only trace amounts of suspended solids were recorded. The temperature of the spent caustic at the time of injection was subject to seasonal variation.

2.5 Need for Subsurface Disposal

Changes to pre-existing process operations at the Winnipeg refinery had already resulted in reduction of waste volumes and number of waste constituents, prior to initiation of subsurface-disposal operations. The costs of further changes in process operations, aimed at waste reduction, could not be justified, in view of plans to shut down the refinery in 1975. For the same reason, construction of waste-treatment plants, such as caustic neutralization facilities, was not considered feasible. Likewise, construction of on-site storage facilities at an approximate cost of $60,000 would have only resulted in postponement of considerations of what to do with the wastes until the time of termination of refinery operations and could hardly be regarded as a mode of disposal. Subsurface disposal was a logical course of action, since it provided a means of isolating the toxic components of the spent caustic solutions from the biosphere.

3. THE DISPOSAL WELL

3.1 General Statement

The economic advantages of using reworked wells, that is, dry holes and former producing wells, for subsurface disposal are significant, particularly when the wells are already completed in the proposed injection unit. Ostroff (1965, p. 165) outlined the main advantages, with the specific case of disposal of oilfield brines in mind, although his comments are equally applicable to the injection of fluid, industrial wastes in a former oilfield production well:

(1) Use of a pre-existing well greatly reduces or largely eliminates well costs.

(2) Operating costs are reduced, since lowered injection pressures are a consequence of pre-injection withdrawal of formation fluids. These factors were important in providing Imperial Oil Limited with a sound economic basis for initiating subsurface disposal of refinery wastes at the Maples production locale.

3.2 Well Construction

The Imperial Virden 7-8M-10-26 well (Lsd 7-8-10-26 W1) was spudded on July 10, 1955, and during the following 8 days was drilled as an oil well in the Maples field, with carbonates of the Mississippian Lodgepole Formation as the drilling target. The mud programme employed a water-bentonite drilling fluid. The casing programme was as follows: 10-3/4-inch, 40.5 lb/ft J-55 surface casing, landed at 513.41 feet K.B. with 300 sacks of 2 per cent $CaCl_2$ cement, and 7-inch, ~~28~~ 20 lb/ft J-55 production casing, set at 2,080 feet K.B. with 175 sacks of 2 per cent gel cement. The 2-1/2-inch production tubing was set at 2,138 feet K.B. The well was given a 6-1/8-inch open-hole completion from 2,080 feet K.B. to a total depth of 2,142 feet K.B., by drilling out the cement shoe, cleaning out the hole and acidizing the open-hole interval with 250 gallons of 15 per cent mud clean-out acid and 500 gallons of 15 per cent hydrochloric acid. The well went on production on March 15, 1956. Production operations were suspended in September, 1962, and the well was approved for abandonment by the Manitoba Mines Branch on December 7, 1967.

For waste injection, a well design, based on that of oilfield pressure-maintenance and salt-water-disposal systems, was favoured. On October 27, 1969, the pump, rods and tubing were pulled and a string of plastic-lined, 2-1/2-inch tubing was landed at 2,059 feet K.B., using a Baker Model A tension packer. The annular space, between the 7-inch casing and the 2-1/2-inch tubing, was filled with fresh water, containing 20 gallons of an inhibitor. The main design elements of the refinery-waste disposal well are shown schematically in Figure 4. The reworked well went

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Fig. 4 - Schematic diagram of the Imperial Virden 7-8M-10-26 disposal well (Lsd 7-8-10-26 W1) and main stratigraphic units penetrated

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on stream for disposal of refinery spent caustic, transported by truck from Winnipeg, on October 29, 1969, and continued to be used for waste injection until October of 1975, when operations ceased, on conversion of the refinery to a product terminal.

3.3 Completion Design

The completion is a 6-1/8-inch open hole from 2,080 to 2,142 feet below K.B. (Fig. 4). This type of completion is commonly adopted for relatively well indurated reservoir rocks, such as the vuggy carbonates of the Lodgepole sequence. Open-hole completion is also favoured, when injection of corrosive wastes is under consideration, since corrosion of both casing and cement would give rise to an accumulation of debris at the bottom of the hole, which in turn would plug the porosity of the disposal interval.

3.4 Projected Abandonment Procedure

Information on a projected abandonment procedure was obtained from Imperial Oil Enterprises Limited in January, 1973, when it was known that both refinery and disposal well would be closed down in 1975. The main abandonment procedures, proposed at that time by J. L. Krushelnitzky and E. M. Ziobrowski (pers. comm. to Simpson, 1973), were:

(1) setting of a Baker Model K cement retainer at 2,030 feet K.B. and squeezing of the open hole with 50 sacks of oilwell cement;

(2) use of a 5-sack cement plug, emplaced on top of the retainer;

(3) filling of the casing with inhibited fresh water;

(4) cutting off of the production and surface casings 3 feet and 4 feet below ground level respectively; and

(5) setting of 5-sack cement plugs on top of each casing, prior to welding of steel plates over each.

At the time of writing the present account, waste injection had already been terminated, but abandonment of the well had not been effected.

3.5 Surface Facilities

Tank-truck deliveries of spent caustic solution from the Winnipeg refinery were pumped out into a surface storage tank (11-1/2 feet by 20 feet) with a capacity of 370 bbl. on the well site. The tank had a closed top and was connected by piping to the well-head. An injection pump

(John Ingles - Worthington KAA, Horizontal Single-Acting Duplex) operated on level control to deliver waste to the well. The capacity of the pump was 3.5 U.S. g/m. An overflow line and tank were provided to prevent spills, in the event of overfilling of the main storage tank. The injection pump was housed within a small shed and all surface facilities were enclosed by an industrial-plant fence, which was kept locked at all times. Figure 5 shows

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Fig. 5 - Surface equipment at the Imperial Virden 7-8M-10-26 disposal site (Lsd 7-8-10-26 W1) in August, 1975

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surface equipment at the refinery-waste disposal site. A general view of the farmland setting of disposal operations is shown in Figure 6.

Fig. 6 - General view of the Maples oilfield, as seen from the waste-injection site

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4. HYDROGEOLOGIC SETTING OF WASTE INJECTION

4.1 General Statement

Detailed descriptions of stratigraphy and distribution of the principal lithofacies, belonging to the Lodgepole Formation (Mississippian) of southwestern Manitoba have been supplied by Stanton (1956), McCabe (1959, 1963, 1967, 1971) and Davies et al. (1962). Aspects of the chemistry of formation brines in Manitoba, including those of the Lodgepole sequence, have been discussed in papers by Porter and Fuller (1959), Bannatyne (1960) and Hitchon (1964). The outline of Lodgepole lithologies and incorporated formation fluids presented below is largely based on these previous accounts.

In southwestern Manitoba, the Lodgepole Formation comprises bioclastic limestones and dolomitic and calcareous shales, which conformably separate the black, bituminous shales of the uppermost part of the Bakken Formation from the relatively coarse-grained, bioclastic, algal, oolitic and pelletoidal limestones of the Mission Canyon Formation. The Mission Canyon and uppermost part of the Lodgepole sequence have been removed by pre-Jurassic erosion at the Maples field, where eroded Lodgepole strata are unconformably overlain by argillaceous red beds of the Jurassic Amaranth Formation. Figure 7 shows structure

Fig. 7 - Structure contours on the Mississippian erosion surface and distribution of oil fields in southwestern Manitoba

contours on the Mississippian erosion surface, as well as the configuration of subcrop belts of the principal reservoir rocks and their relation to distribution of the main oil production locales.

The Lodgepole and Mission Canyon Formations are reservoir rocks for crude oil in southwestern Manitoba, where they are truncated at the sub-Mesozoic unconformity. Relatively impermeable Jurassic red beds, resting on the erosion surface, and patterns of dolomitization and anhydritization in the Mississippian strata immediately below the unconformity constitute the cap rocks; the seat seal is provided by shales of the Bakken Formation. Structure is also an important factor, controlling patterns of oil accumulation in southwestern Manitoba and exerts a strong influence, notably at the largest fields (Daly, North Virden - Scallion, Virden Roselea and Routledge), in the form of amoeboid folds, some of which are truncated at the sub-Mesozoic unconformity. The folds are a result of localized collapse, attendant upon solution of Middle Devonian evaporite strata and in the Virden district range in age from post-Mississippian and pre-Amaranth to post-Favel (Turonian). As shown in Figure 7, the Lodgepole subcrop belt rises structurally to the northwest in the Virden district; at Maples, production of crude oil is obtained from a minor fold in the subcrop belt.

4.2 The Disposal Interval

The upper part of the Lodgepole Formation exhibits systematic, vertical variation in the amount of calcareous shale interbedded with limestones. This succession is divided into 2 units, each of which comprises regularly alternating layers of oolitic limestone and calcareous shale, replaced upward by crinoidal, fossil-fragmental limestones with subordinate fine-grained intercalations. These units are the Virden Member and succeeding Whitewater Lake Member which together constitute the reservoir strata for Lodgepole oil production in southwestern Manitoba (Table 3). They exhibit progressive westward decrease in

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Table 3 - Generalized reservoir characteristics of the Lodgepole Formation at the Maples field

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grain size of the relatively coarse-grained limestones, which is accompanied by a gradual increase in number and thickness of the calcareous shale intercalations. The lower part of the Lodgepole sequence comprises fine-grained arenaceous limestones, grading westwards into argillaceous limestones and calcareous shales (Scallion Member), resting locally on black shales (Routledge Shale). The relationship between Lodgepole isopachs, the Lodgepole subcrop belt and the distribution of shale facies in the lower part of the formation is shown in Figure 8.

Fig. 8 - Isopachous map of the Lodgepole Formation in the Williston basin region

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The open-hole completion of the Maples disposal well penetrates some 25 feet of generally tight, argillaceous dolomite with subordinate chert and anhydrite, resting on 37 feet of sporadically vuggy limestones, also containing minor chert and anhydrite (Appendix I). The dolomitized part of the open-hole section is referred to the lowermost part of the Whitewater Lake Member. Reservoir quality improves greatly in the limestones beneath, which are referable to the Upper Virden Unit of the Virden Member of the Lodgepole Formation. This unit is termed "Crinoidal" in the oilfield district of southwestern Manitoba and yields production of light crude oil (30 to 35° API) at the Maples, North Virden-Scallion, Virden-Roselea and West Routledge fields. Structure contours on the Lodgepole Formation in the Maples field are shown in Figure 9. The distribution

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Fig. 9 - Structure contours on the Lodgepole Formation in the Maples oilfield, southwestern Manitoba

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of the principal Lodgepole reservoir lithologies in the Maples field is presented in Figure 10. The lithologies of

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Fig. 10 - Fence diagram showing distribution of main Upper Lodgepole lithofacies in the Maples oilfield, southwestern Manitoba

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the disposal interval and superjacent strata are shown in Figure 11. The vuggy porosity of the Upper Virden unit is

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Fig. 11 - Core from the disposal interval and superjacent strata in the Lodgepole Formation of the Imperial Virden 7-8M-10-26 well (Lsd 7-8-10-26 W1)

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particularly striking in the basal 17 feet of the cored section, where individual vugs have diameters of up to 2 inches (Fig. 12).

Fig. 12 - Vuggy porosity in bioclastic, argillaceous limestone of the disposal interval, Virden Member of the

Lodgepole Formation, 2,--- feet, Imperial Virden 7-8M-10-26 well (Lsd 7-8-10-26 W1)

4.3 Confining Lithologies

The capping lithologies of the Maples oil reservoir have fulfilled a confining function in the vicinity of the disposal well, thus restricting migration of the spent caustic plume to parts of the Whitewater Lake and Virden Members with improved reservoir quality. The cap rocks are the fine-grained Amaranth red beds, which overlie the truncated Lodgepole strata, and the more strongly indurated parts of the Lodgepole sequence immediately beneath the unconformity, which have undergone extensive dolomitization and anhydritization. Fine-grained dolomite and interbedded anhydrite, as well as subordinate chert in nodules and lenses (Fig. 13), occur as cap rock, major heterogeneities

Fig. 13 - Dolomite and interbedded anhydrite as reservoir heterogeneities, Lodgepole Formation, 2,--- feet, Imperial Virden 7-8M-10-26 well (Lsd 7-8-10-26 W1)

between strata of good reservoir quality (such as the lower parts of Upper Lodgepole members), and as minor heterogeneities within the reservoir units.

The thickness of dolomitized Mississippian rocks under the sub-Mesozoic erosion surface appears to have been a function of variation in thickness of Lower Amaranth argillaceous red beds, which separate the Mississippian strata from a succession of Upper Amaranth evaporites (Young and Greggs, 1975). The dolomitization process was seemingly one of downward percolation of hypersaline brines, which took place during sedimentation of the Upper Amaranth anhydrite beds (Young and Greggs, op. cit.), so that dolomitized Mississippian strata attain greatest thicknesses, where the Jurassic red beds are relatively thin or totally absent. Clearly original porosity-permeability gradients in the uppermost Mississippian strata and the palaeotopography preserved at the erosion surface would exert considerable influence on the circulation patterns of the hypersaline brines (McCabe, 1959). Detailed petrographic study by Young and Greggs (op. cit.) suggests that anhydrite precipitation in the Virden Member followed dolomitization and involved movement of sulphate waters down fractures related to salt-solution collapse of strata.

Additional geological factors, controlling the containment of the injected refinery wastes, are (1) the progressive westerly decrease in grain size of the Upper Lodgepole disposal aquifers and related deterioration in permeability and (2) the relatively fine-grained nature of the Lower Lodgepole sequence and reduced permeability of both these deposits and the Bakken shales beneath.

4.4 Formation Fluids

Subsurface brines of the northern Williston basin region undergo progressive increase in concentration with depth, so that the highest total dissolved solids and chloride contents are encountered in the basal part of the sedimentary sequence at depths in the order of 10,500 feet below surface in the Williston basin proper (Porter and Fuller, 1959; Bannatyne, 1960; Hitchon, 1964). The Mississippian Lodgepole Formation is characterized by formation brines with total dissolved salt contents of up to 200,000 ppm; relatively high values in the range 150,000 to 200,000 ppm total dissolved solids are restricted to the Virden district, the Daly field and vicinity and a belt, several townships wide, along the Forty-ninth Parallel (Bannatyne, op. cit., Fig. 8, p. 23). This distribution of relatively high brine concentrations is closely comparable to that also obtained by Bannatyne (op. cit.) for the Nisku Formation (Devonian) and the Mission Canyon Formation (Mississippian) in southwestern Manitoba. It is noteworthy that Bannatyne (op. cit.) plotted only analyses giving total dissolved solids contents of more than 125,000 ppm on his maps of brine concentration.

Table 4 presents the results of a water analysis by

Table 4 - Composition of formation brines from the Lodgepole Formation in the Imperial Virden 7-8M-10-26 well (Lsd 7-8-10-26 W1)

Chemical and Geological Laboratories Ltd., Regina, of a sample taken from the Upper Lodgepole sequence, penetrated by the Maples disposal well. The variations in total dissolved solids and chloride content in the Lodgepole Formation of southern Manitoba are shown in Figures 14 and

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Fig. 14 - Total dissolved solids in brines of the Lodgepole Formation, southern Manitoba

Fig. 15 - Chloride content of brines of the Lodgepole Formation, southern Manitoba

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15 respectively. The analysis of brine from the Maples disposal well indicates relatively low Ca, Mg, Na and K, and Cl but relatively high HCO_3 contents, by comparison with values listed by Bannatyne (1960) for brines from a variety of Paleozoic units in Manitoba. The specific gravity of the Lodgepole brine is 1.040 and is intermediate in value between that of the refinery waste (about 1.1) and the crude oil (0.845 at 60°F). Charbonnier et al. (1969) record 1.39 per

cent sulphur in an oil sample from the Maples field; the same sample yielded 8.7 per cent by volume light gasoline, 27.1 per cent total gasoline and naphtha and 5.1 per cent kerosene distillate.

4.5 Reservoir Hydrodynamics

The potentiometric surface for brines in the Lodgepole Formation of southwestern Manitoba is shown in Figure 16. Results of drill stem tests at wells drilled to

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Fig. 16 - Potentiometric map of brines in the Lodgepole Formation of southern Manitoba

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the disposal unit in the vicinity of the injection well are presented in Table 5.

Table 5 - Results of drill stem tests at wells drilled to the Lodgepole Formation near the Imperial Virden 7-8M-10-26 well (Lsd 7-8-10-26 W1)

Berg (1956) and McCabe (1963) demonstrated that the edge-water interface maintains a constant elevation within a given reservoir unit and that this elevation may take on different values from one unit to another. For example, McCabe (<u>op</u>. <u>cit</u>., p. 24) gave 670 to 680 feet below sea level as the approximate minimum elevation of the oil/water interface for all reservoir beds in the southwestern part of the Virden producing district. The -670-foot contour on the Upper Virden Unit marks the approximate position of the edge water for that reservoir unit, while the -710-foot contour defines edge water for the Whitewater Lake reservoir. To the southwest of these contours, each reservoir unit drops below its oil/water interface. Northward from the Maples locale, the oil/water interface undergoes a net rise to between -600 and -620 feet near Sec. 18, Twp. 11, Rge. 26, interrupted by water-bearing synclinal features, similar to the one in the northeastern corner of the Maples field. Water encroachment in the vicinity of the Maples disposal well during its oil-production history has ensured separation of the refinery wastes from the oil produced up-dip during later use of the well.

4.6 Wastes in the Subsurface Environment

Laboratory tests were carried out by Imperial Oil Limited to determine if the spent caustic solutions would react with Lodgepole brines to produce precipitates, which could plug the porosity of the disposal unit. These tests were made in May, 1969, and involved mixing of 50 ml samples of spent caustic solutions, representing a wide variety of types of solution, with 50 ml of Lodgepole brine, obtained from 2 wells located near the disposal well. Table 6 shows

Table 6 - Results of compatibility tests employing mixtures of refinery wastes and brines from the Lodgepole Formation in the Imperial Maples 8-8-10-26 well (Lsd 8-8-10-26 W1)

the results of the tests performed using brine samples from the Lodgepole Formation, where it is penetrated by the Imperial Maples 8-8-10-26 well (Lsd 8-8-10-26 W1). As much as 273 mg of precipitate was formed by the waste-brine reactions. An important purpose of the tests was to find a solvent for precipitates thus formed and it was shown between 77.9 and 100 per cent of the precipitate samples by weight were soluble in 15 per cent hydrochloric acid. Similar results were obtained when spent caustic solutions were mixed with equal amounts of Lodgepole brine from the Imperial Haskett 13-2-10-28 well (Lsd 13-2-10-28 W1). No attempt appears to have been made to simulate reservoir conditions of increased temperature (82°F at about 2,129 ft. below surface) and pressure (948 psig).

5. OPERATION HISTORY OF DISPOSAL WELL

5.1 General Statement

To the economic and information-oriented advantages of converting an existing, suspended production well in an oilfield location for use as a waste-injection well, noted in the preceding chapters, should be added one more, relating to increased safety of operation of such a disposal facility. Production of crude oil and associated formation brines from the pay zone (disposal interval) through the well prior to reworking resulted in a reduction in reservoir pressure, where the unit is transected by the well bore. This was augmented by a general depletion of pressure of the reservoir as a whole, arising as a cumulative effect of pumping from all current and former production wells in the field. The decrease in reservoir pressure, thus obtained, permitted emplacement of the refinery waste at 0 psig injection pressure, minimizing the risk of fracturing the disposal formation and confining beds.

5.2 Well History Prior to Waste Injection

Production of light crude oil from the Imperial Virden 7-8M-10-26 well (Lsd 7-8-10-26 W1) began on March 15, 1956. Cumulative oil production for March amounted to only 613 bbls and water accounted for 82 per cent of the total volume of fluid produced. Water as a percentage of total volume of fluids withdrawn increased to 90 per cent in March 1957, and to 98 per cent in September, 1959. The last production was obtained from the well in September, 1962; at that time, the total cumulative production amounted to 21,339 bbls of crude oil and 478,370 bbls of water. The maximum permissible oil recovery for the well was 34 bbls/day, although the highest average oil production obtained in any month was 24 bbls/day, attained on several occasions in 1957. The maximum total water production for any month was 10,967 bbls, withdrawn in January, 1961, when 124 bbls of crude oil were also recovered. The fluid-production history of the well is summarized in Figure 17. The

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Fig. 17 - History of oil production and water production from the Imperial Virden 7-8M-10-26 well (Lsd 7-8-10-26 W1).

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tendency to water out early in the production history is characteristic for wells obtaining production from the Lodgepole Formation in the Maples pool. Figure 18 shows the

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Fig. 18 - History of oil production and water production at the Maples field, southwestern Manitoba

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fluid-production history of the Maples field as a whole.

5.3 Water-Injection Test

Water-injection operations were preceded by a water injection test, in which 1,000 bbls of fresh water were pumped into the disposal interval as a buffer pad. Injection of a buffer fluid into a disposal well before introduction of the waste effluent serves 2 main purposes:

(1) to test the efficiency of the well equipment; and

(2) to keep the plume of injected wastes from making direct contact with formation fluids, thus preventing chemical reactions, which might result in a loss of porosity through the formation of plugging precipitates.

Use of fresh water as a buffer fluid is widely practiced by disposal-well operators and was adopted at the Maples disposal site, as a result of the possible incompatibility between the refinery wastes and Lodgepole brines, suggested by the laboratory tests, outlined in Section 4.6. A portable pump was used to inject 1,000 bbls of fresh water at rates and pressures in the range 1-1/3 bbls/m at 100 psig to 3-1/2 bbls/m at 900 psig on October 27, 1969. The results of the test are summarized in Figure 19. On cessation of water injection, 200 bbls

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Fig. 19 - Results of water-injection tests in the Imperial Virden 7-8M-10-26 well (Lsd 7-8-10-26 W1).

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of refinery waste were pumped down the well at the same rates and pressures, after which the well was kept on vacuum at an injection rate of 1/3 bbl/m. As noted below, it is possible that the buffer pad did not prevent mixing of the spent caustic and the Lodgepole brines, since there is evidence of some reaction having taken place.

5.4 Waste-Injection History

The Imperial Virden 7-8M-10-26 well (Lsd 7-8-10-26 Wl) went on stream as a refinery-waste disposal well on October 29, 1969. With the injection tubing filled by spent caustic waste, the hydrostatic head in the well was adequate for introduction of further waste at 0 psig (gravity feed). Subsequent injection was at an average rate of 3.5 US g/m. The injection history of the Maples well is summarized in terms of volumes of injected fluid in Figure 20.

Fig. 20 - History of waste injection at the Imperial Virden 7-8M-10-26 well (Lsd 7-8-10-26 Wl).

A decline in well performance, probably due to the plugging of pore space by precipitate, resulting from effluent-brine reactions, led to acidizing of the open-hole interval on June 16, 1970. The acid job involved injection of 250 gallons of 28 per cent hydrochloric acid at 3 bbls/min and 600 psig. The well was then placed back on stream and no further loss of reservoir quality was recorded.

5.5 Operational Safeguards

The disposal facility was checked daily, whenever it was in use. Quantities of spent caustic introduced into the well were measured by means of trucking weights. The limited capacities of both the well-site storage tank (370 bbls) and the injection pump (3.5 US g/m) imposed severe constraints on injection rate. At no time in the history of the Imperial Virden 7-8M-10-26 well (Lsd 7-8-10-26 Wl) had the Lodgepole sequence been fractured and it is noteworthy that the pump, employed in disposal operations, was incapable of delivering injection pressures, high enough to fracture the disposal reservoir. Pre-injection withdrawal of formation fluids had resulted in a loss of reservoir pressure, which in turn permitted waste injection at gravity feed throughout the life of the disposal well. Thus at the Maples disposal site, the potential hazards, related to inadvertent hydraulic fracturing of the disposal unit[1], discussed by Wolff *et al*.

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[1] The pressure, resulting from overburden load within a sedimentary sequence, is frequently estimated as 1.0 psig/ ft of depth below surface (Clark, 1966). Hydraulic

fracturing tests by Wolff _et al_. (_op_. _cit_.) indicate that vertical fractures may be induced at an injection pressure of about two-thirds of the total overburden load, that is, 1,400 psig at the Maples disposal site.

The wastes were confined within the plastic-lined tubing string. The production casing would have served as a secondary safety string, in the event of a tubing failure, while the surface casing constituted a tertiary protection string for near-surface aquifers, containing potable water. Corrosion rates were measured by means of corrosion coupons and no significant corrosion was detected. No observation wells were drilled to shallow aquifers, but a shallow water well, located a quarter of a mile from the disposal well, was used by the landowner and no contamination of the water supply was ever detected. Similarly, although no deep observation wells were drilled to the disposal interval, no effects were observed in neighbouring oil wells, also drilled to the Lodgepole carbonate sequence.

Emergency storage facilities, both at the refinery and at the disposal site, provided a possible minimum of 12 days' storage for the waste spent caustic. Thus the total storage capacity available was adequate to permit maintenance and repair of the disposal facilities. Any leakage from surface installations at the disposal site would have been detected visually by the battery operator during his daily visits to the disposal locale.

5.6 Possible Environmental Impact

Monitoring of the effects of refinery-waste injection at the Maples site was minimal and was largely dependent on thorough visual inspection of surface installations by the local operator. Continuous records of injection pressure and/or injection rate are widely employed at Canadian waste-injection systems (Simpson, 1975) to provide an indication of both well efficiency and waste behaviour in the subsurface. The low priority assigned to continuous monitoring at the wellhead of the Maples disposal facility seems justified in the light of waste introduction at gravity feed and at low rates of 3.5 US g/m or less under conditions of depleted reservoir pressure and over a predetermined, relatively short time period of 6 years. The oilfield location of the Maples disposal well and related possibility of detecting increases in reservoir pressure by means of observations on current producing wells offered a rare opportunity to record injection-induced changes in subsurface movement of fluids, especially since observation wells to disposal intervals are scarce in Canada (Simpson, *op. cit.*). However, at the time of writing this report, no increased formation pressures had been noted in producers, located near to the disposal well; nor was any contamination of the crude oil, produced from the Maples pool, detected. Indeed, repressurization of the oil reservoir as a result of waste injection would have the beneficial effect of enhancing oil recovery, comparable to the use of sewage effluent as a waterflood medium, described by Simmons (1957). The down-dip location of the disposal well in relation to current producers of the Maples field largely eliminates the possibility of mixing of the spent caustic solutions and the crude oil being produced.

5.7 Comparison with Other Refinery-Waste Injection Operations

The Maples disposal well is 1 of 35 such facilities, injecting refinery wastes into subsurface strata, in 4 Canadian provinces: 15 of these wells are in southwestern Ontario, 1 in Manitoba (Maples), 2 in Saskatchewan and 17 in Alberta. The oil-refining industry has traditionally led the way in initiation of subsurface-disposal operations in 3 of the 4 provinces: Husky Oil Operations Limited at Lloydminster, Alberta, in 1949; and Imperial Oil Enterprises Limited at Sarnia, Ontario, in 1958; at Regina, Saskatchewan, in 1963[1]; and at the Maples field, Manitoba, in 1969. Of

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[1] In Saskatchewan, the first refinery-waste injection operations followed initiation of 3 salt-cavern-brine

disposal wells and 5 pilot potash-brine disposal wells (Simpson and Dennison, 1975).

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the 35 refinery-waste injection facilities in Canada, 27 dispose of wastes into carbonate aquifers, the remainder into siliciclastic reservoir rocks. The shallowest Canadian disposal wells were operated from 1958 to 1970 by the Imperial Oil Limited refinery at Sarnia, Ontario, and utilized an injection interval at about 635 to 800 feet below K.B. The deepest Canadian disposal well, the Dow 3 Ft. Sask. NaCl 10-10-55-22 well (Lsd 10-10-55-22 W4) in central Alberta injects refinery wastes into reservoir strata at depths of 5,378 to 6,175 feet below K.B. Only in Manitoba and Alberta are refinery wastes injected into the reservoir strata of hydrocarbon-producing locales; Alberta has 8 such facilities.

6. ECONOMICS OF SUBSURFACE DISPOSAL

6.1 General Statement

Deep-well injection of fluid, industrial wastes at surface locations, in close proximity to the waste-generating processes (on-site disposal), minimizes waste-handling problems and has obvious, related cost-saving advantages for operators. Clearly, risk of contamination of surface waters by wastes, predesignated for deep-well injection, is a function of not only waste volume and composition and rate of waste production, but also of the number of steps in pre-injection handling of the wastes and the duration of each step (Table 7). On-site waste injection reduces both

Table 7 - On-site waste injection vs. off-site waste injection: Main factors controlling risk of pre-injection contamination of surface waters.

the number of steps in waste movement from source to wellhead and the total time of travel, as compared with systems, involving transportation of wastes over relatively large distances to the injection site (off-site disposal). On the other hand, off-site waste disposal increases the number of options, relating to the choice of disposal interval, and thus removes restrictions on subsurface disposal, imposed by the geological setting of waste-source process. The increased choice of disposal interval presents the possibility of increased safety of waste injection.

6.2 Transportation Costs

The Maples disposal well is located some 175 miles from the Imperial Oil refinery in Winnipeg. Access is along the Trans-Canada Highway (Manitoba Rte. 1), Manitoba Rte. 83 and a gravel road, which is part of the system of grid roads serving the Maples oilfield. The wastes were moved by tank truck to the wellhead at an average rate of 30 bbls per day and at a cost of about $800 per month, that is, at a cost of about 88 cents per barrel.

6.3 Disposal Costs

Reworking of the Imperial Virden 7-8M-10-26 oil well (Lsd 7-8-10-26 W1) eliminated costs, relating to land acquisition and drilling, testing and casing of the well. At the time the well was drilled in 1955, these costs amounted to $37,391. The total cost of storage tanks, the pump and motor of the disposal well, as well as the shed, housing the wellhead, the fence, surrounding it, and the roadway was about $20,000 in 1969/70. Operator costs during use of the well were about $120 per month. Approximate abandonment costs, in accordance with the proposal scheme of abandonment, outlined above, were $2,500.

Fluid withdrawal from the Maples well prior to waste injection resulted in a reduction in reservoir pressure, which in turn permitted introduction of the wastes at gravity feed and minimal use of pump power.

6.4 Estimated Costs of Alternative Modes of Disposal

The cost of a storage tank to contain the spent caustic solution on-site up to the time of shutdown of the Winnipeg refinery was estimated to be approximately $60,000. The installation of on-site neutralization facilities could not be considered as a viable alternative course of action, in view of the 1971 announcement that the Winnipeg refinery would be converted to a petroleum-product distribution terminal, and consequently no costs for such facilities were estimated. These costs would have been in the order of several hundred thousands of dollars.

6.5 Ultimate Capital Investment

The ultimate capital investment, estimated for the disposal well, was given as $61,000. This figure clearly does not include the monthly trucking and operating cost of $920, which would give a total of $66,240 over the 6-year injection history of the well. Thus the overall cost of waste injection at the Maples well was approximately $127,240.

7. CONCLUDING REMARKS

1. In 1969, a decision was made by Imperial Oil Enterprises Limited to dispose of phenol-rich, spent caustic solutions from the company's Winnipeg refinery by injection into a subsurface aquifer. This mode of disposal was not feasible at the refinery site, because of the high risk of polluting metropolitan Winnipeg's ground-water supplies. Instead the wastes were transported by road some 175 miles to the Imperial Virden 7-8M-10-26 well (Lsd 7-8-10-26 Wl), where they were injected into carbonates of the Lodgepole Formation (Mississippian) from 2,080 to 2,142 feet below K.B. Disposal operations began in October, 1969, and were terminated in October, 1975, when the refinery was shut down.

2. The disposal well was a reworked, suspended oil producer in the Maples field. Prior to conversion the well yielded 21,339 barrels of crude oil and 478,370 barrels of formation brine from the Lodgepole pay zone. In 6 years of operation as a disposal facility, the well was used to emplace some xx,xxx barrels of spent caustic solution into the upper part of the Lodgepole Formation at a rate of 3.5 US g/m and 0 psig (gravity feed). Although laboratory work by Imperial Oil personnel suggested the existence of

incompatibility between the injected wastes and the Lodgepole brines, disposal-formation porosity has not been impaired in the vicinity of the well bore.

3. The open-hole interval of the disposal well comprises 25 feet of reddish, finely porous, argillaceous dolomite, locally fossiliferous and incorporating thin layers of subordinate anhydrite and chert, referable to the Whitewater Lake Member, which rests on 37 feet of grey to buff, dominantly argillaceous, bioclastic limestones with chert intercalations and minor anhydrite as nodules, thin layers and fracture infillings, belonging to the Upper Virden Unit (the "Crinoidal" of the oilfield district) of the Virden Member of the Lodgepole Formation. The basal 17 feet of reservoir strata have coarse, vuggy porosity. The reservoir rocks as a whole exhibit a westerly decrease in grain size, porosity and permeability. The Lodgepole succession is overlain unconformably by fine-grained red beds, belonging to the Lower Member of the Jurassic Amaranth Formation. The Maples field obtains production of crude oil from a structural-stratigraphic trap, defined by spatial coincidence of Lodgepole carbonates with good reservoir quality and one of a series of positive structural features, related to differential collapse, attendant upon localized solution of Middle Devonian evaporite beds. The

disposal well penetrates the Upper Virden Unit at a location, down-dip with respect to current producers of the Maples field.

4. Successful waste injection at the Maples locale suggests that use of reworked producing wells in oilfield settings holds a number of definite advantages for disposal well operators:

(a) Use of a pre-existing well greatly reduces or largely eliminates well costs.

(b) Operating costs are reduced, since lowered injection pressures are feasible in settings of depleted reservoir energy, arising from the pre-injection withdrawal of formation fluids.

(c) Reduced reservoir pressures at a production locale lower the risk of fracturing the disposal interval and confining beds during operation of a waste-injection facility.

(d) The good well control, usually obtained at oil production locales, permits relatively accurate delineation of trends in reservoir quality, so that patterns of waste migration may be predicted.

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