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The Fort Garry Aquifer in Manitoba

By R.N. Betcher, H.R. McCabe, and F.W. Render

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ABSTRACT

The Fort Garry aquifer is a persistent interval of enhanced permeability found in the Fort Garry Member of the Ordovician Red River Formation which forms part of a major Paleozoic carbonate rock aquifer system in southern and central Manitoba. Test drilling, geophysical logging and examination of cores has shown that the high permeability in this stratigraphic interval results primarily from the presence of widespread solution features. These features are thought to have originated during one or more periods of strong erosion and karst development which affected southern Manitoba from the late Silurian until the present. Preferential development of solution features in the Fort Garry Member appears to be related to dissolution and removal of thin but widespread anhydrite beds within this Member, creating pathways for the movement of groundwaters and subsequent development of karst dissolution features.

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INTRODUCTION

Paleozoic rocks, consisting of a gently dipping interlayered sequence of carbonates, shales and evaporites form a major bedrock aquifer system in southern and central Manitoba (Fig. 1). The eastern and northern portions of this system supply large volumes of fresh to brackish water used for municipal, industrial, agricultural and private supplies. It is estimated that the aquifer system provides as much as 30 000 cm of water per day for consumptive use and considerably more water for non-consumptive heating and air conditioning use.

Observations of bedrock outcrops and experience gathered during drilling indicate that fractures, joints, bedding plane separations and solution enlarged openings (for simplification, all will be included in the term "fracture") provide the major permeable pathways for fluid movement in the aquifer system. Extensive fracturing is frequently observed in the upper few metres of bedrock outcrop in excavations (Fig. 2). This zone provides moderate to large yields of groundwater to wells in many parts of the aquifer system. Fracturing near the bedrock surface may be a result of glacial stresses during the Pleistocene (Trainor 1973), or it may reflect pre-Pleistocene weathering and fracture development which was not removed during glacial erosion. At greater depths, groundwater inflow to wells has been observed to originate from discrete fractures or fracture zones which are separated by intervals of rock having very low permeability. In some areas, enhanced permeability has been recognized to be associated with specific stratigraphic intervals (M. Rutulis personal communication) while in other localities certain strata appear to be consistently poor groundwater production zones (Render 1970). Generally however, little work has been done in Manitoba which attempts to place intervals of enhanced fracture permeability encountered below the zone of bedrock surface fracturing into a stratigraphic framework. In this paper we present results from water well records, test drilling, examination of bedrock outcrops and cores, and borehole geophysical studies which indicate that the Fort Garry Member of the Red River Formation is a persistent zone of enhanced permeability in the carbonate rock aquifer system throughout much of southern Manitoba.

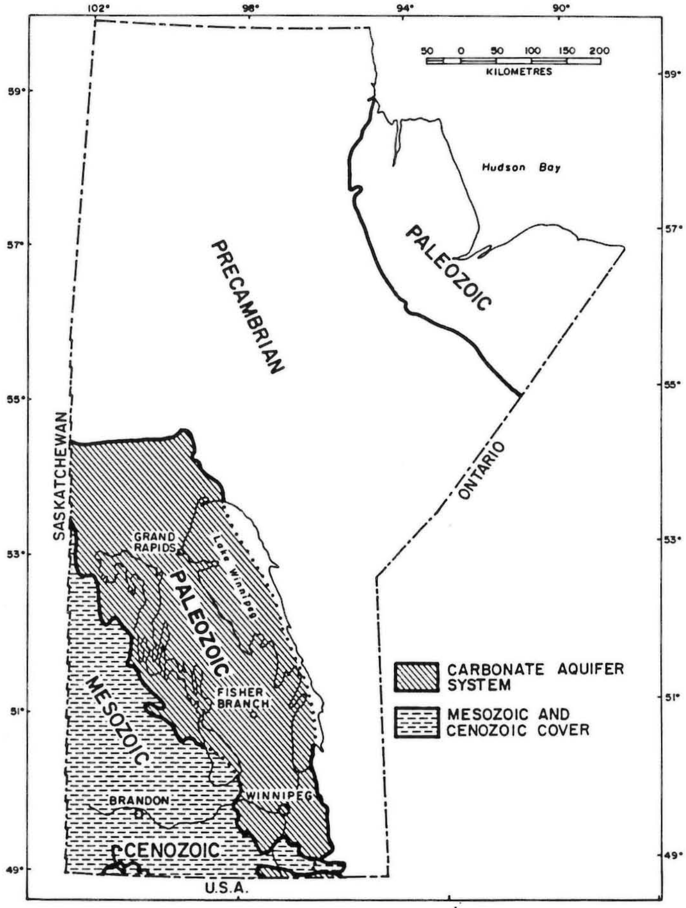

Figure 1: *Location map of the study area showing the distribution of Paleozoic sediments forming the carbonate aquifer system in southern and central Manitoba.*

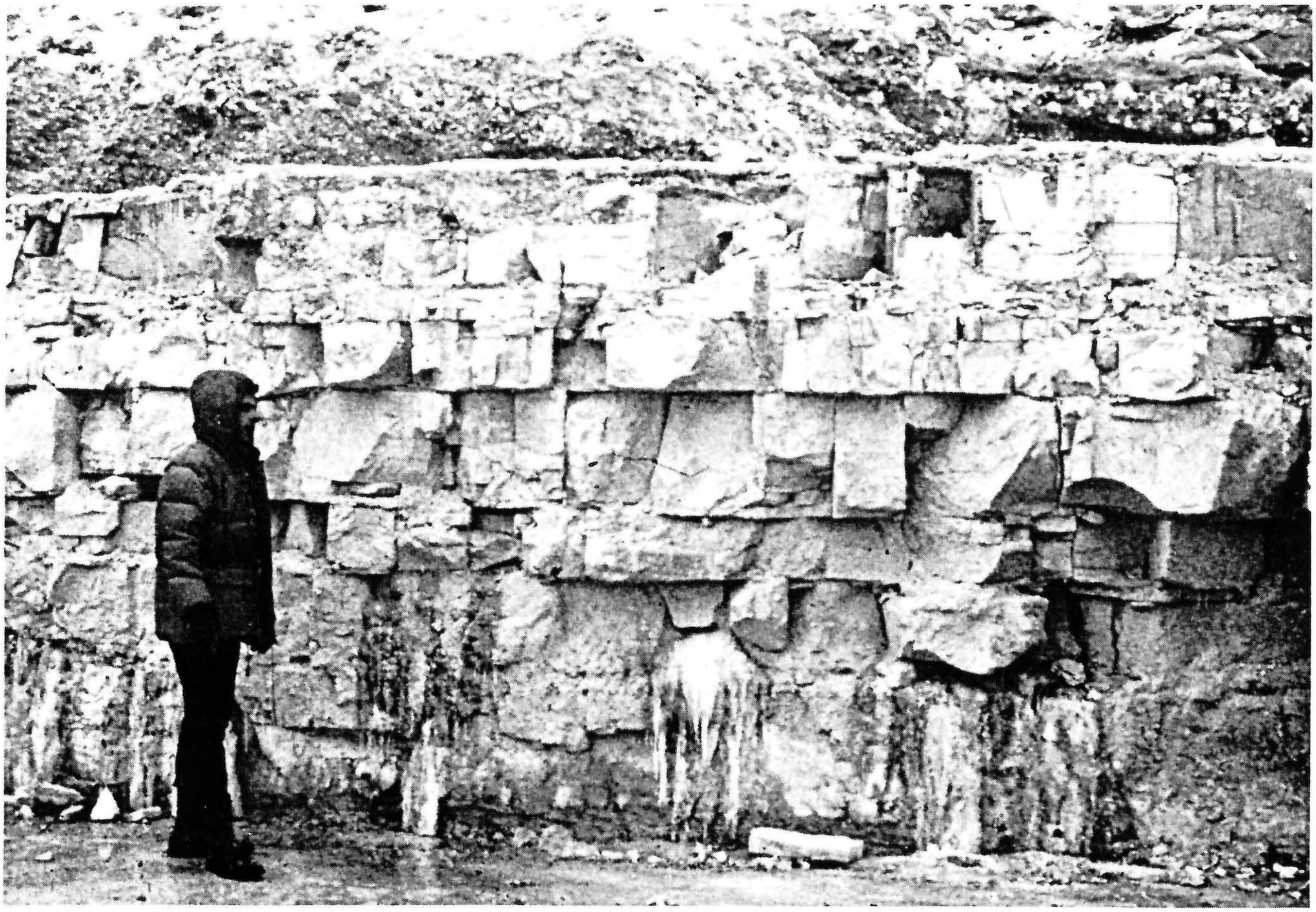

Figure 2: Highly fractured nature of the carbonate rock aquifer at the bedrock surface. Wells completed in this zone commonly produce very large yields.

GEOLOGY

The carbonate rock aquifer system in Manitoba is formed by an interlayered series of carbonate rocks, shales and evaporites (Table 1). The rocks are of Ordovician through Mississippian age and extend throughout the western and central portions of southern Manitoba (Fig. 1). These rocks form part of the eastern edge of the Western Canada Sedimentary Basin and include part or all of the Cambrian-Ordovician and Madison aquifer systems identified by Downey (1984) in the northern great plains region of the United States. The sediments were deposited in a slowly subsiding basin which experienced periodic episodes of more rapid subsidence or uplift. The rocks dip gently to the west or southwest and are truncated towards the east, exposing progressively older sediments in this direction (Fig. 3).

In western and parts of south-central Manitoba the carbonate aquifer system is overlain by Mesozoic and Cenozoic shales, sandstones and evaporites which form an upper confining horizon. The base of the aquifer system is formed by the upper shales of the Winnipeg Formation which act as an effective aquiclude in most of southern Manitoba (Betcher, 1986). In the northern part of the sedimentary basin the upper shales of the Winnipeg Formation are absent and sands of the Winnipeg Formation are included in the carbonate aquifer system. The base of the aquifer system is formed by the Precambrian basement in this area. The portion of the aquifer system covered by Mesozoic sediments is referred to as the subcrop area while the portion not covered by Mesozoics is termed the outcrop area.

The entire sedimentary basin sequence is overlain by Pleistocene and Recent sediments consisting of glacial tills, glaciofluvial and glaciolacustrine sediments and organic, alluvial and beach deposits.The thickness of these deposits varies from zero to more than 100 m.

RED RIVER FORMATION

The Red River Formation forms the basal depositional unit of the Paleozoic carbonate sequence. It is underlain by shales and sandstones of the Winnipeg Formation and is overlain by the carbonates and argillaceous carbonates of the Stony Mountain Formation (Table 1). The Red River Formation consists of a basal sequence of shelf-type bioclastic dolomitic limestones and an upper sequence of

Table 1: Geology of the carbonate rock aquifer system in Manitoba

ERA	PERIOD	FORMATION (Group)	MEMBER	BASIC LITHOLOGY	THICKNESS (m)
		MESOZOIC AND CENOZOIC SEDIMENTS			
PALEOZOIC	Mississippian	Charles		Dolomite and anhydrite.	0 - 35
		Mission Canyon		Limestone, dolomite, anhydrite, oil production.	80 - 100
		Lodgepole	Whitewater Lake Virden Scallion Rouledge	Limestone, argillaceous and cherty; shale; oil production.	145 - 175
		Bakken		Black shale and siltstone.	10 - 15
	Devonian	Lyleton		Red dolomitic shale.	10 - 55
		Nisku		Fossiliferous limestone and dolomite.	10 - 45
		Duperow		Shaly limestone, dolomite, anhydrite; cyclical	120 - 195
		Souris River		Limestone, evaporite, shale; cyclical.	65 - 95
		Dawson Bay		Limestone, anhydrite, basal red shale.	45 - 65
		Prairie Evaporite		Halite, with potash, anhydrite, dolomite.	0 - 130
		Winnipegosis		Dolomite, reef and inter-reef.	10 - 105
		Elm Point		High calcium limestone	0 - 15+
		Ashern		Dolomite and shale, brick red.	2 - 20
	Silurian	Interlake Group		Dolomite	55 - 115
		Stonewall		Dolomite	10 - 20
	Ordovician	Stony Mountain	Gunton Penitentiary Gunn	Dolomite, upper part shaly. Argillaceous dolomite. Fossiliferous calc. shale; red, gray, green.	30 - 50
		Red River	Fort Garry Selkirk Cat Head Dog Head	Dolomite, minor limestone. Dolomitic limestone, mottled. Dolomite, cherty. Dolomitic limestone, mottled.	50 - 150
		WINNIPEG FORMATION (ORDOVICIAN) AND PRECAMBRIAN			

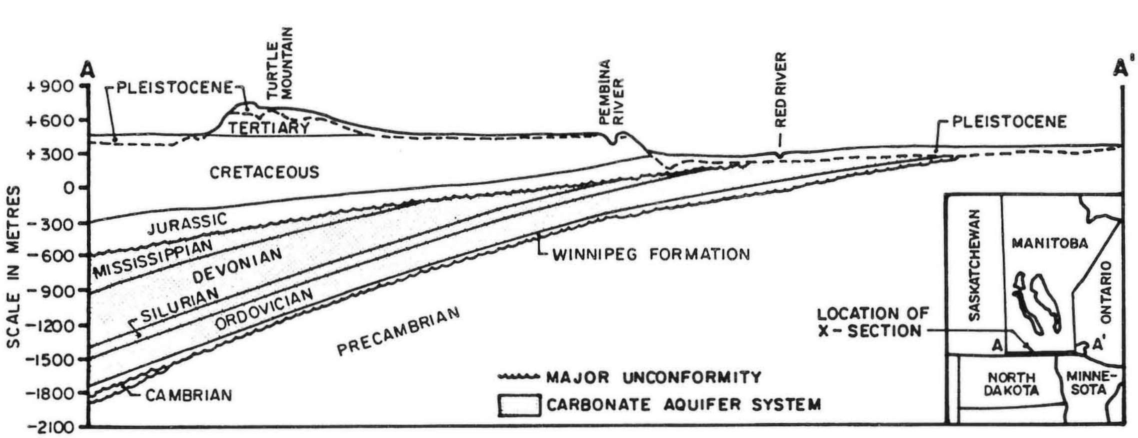

Figure 3: *Cross-section showing sediments of the Western Canada Sedimentary Basin in southern Manitoba. (Modified from Manitoba Mineral Resources Division, 1979).*

dolomitic limestones and lithographic to sublithographic dolomites (Porter and Fuller, 1959; Andrichuk, 1959). The Formation thickness varies from approximately 50 to 150 m with rapid thinning occurring towards the north (McCabe, 1971). In western Manitoba and extending into central Manitoba, upper Red River sediments include two or three recognized anhydrite beds occurring as part of cyclic limestone-dolomite-anhydrite deposition during a series of marine regressions and transgressions near the end of Red River deposition (Porter and Fuller, 1959). The present extent of anhydrite beds is shown on Figure 4 (after Porter and Fuller, 1959) although recent unpublished information indicates that the eastward extent of anhydrite in the central part of the study area may not be as extensive as is shown. Widespread deposits of argillaceous materials in the middle and lower parts of upper Red River sediments form prominent marker beds on natural gamma geophysical logs.

The Red River Formation has been subdivided into four members, in ascending stratigraphic sequence being the Dog Head, Cat Head, Selkirk and Fort Garry (McCabe, 1971). The three lower members are subdivisions of the basal carbonates with the Dog Head and Selkirk Members consisting largely of mottled dolomitic limestone and the Cat Head a more highly dolomitized interval. In central and northern Manitoba this entire sequence becomes completely dolomitized. The Fort Garry Member roughly approximates the upper Red River sedimentary sequence discussed above. In the outcrop area it consists of fine grained dolomites and argillaceous dolomites with local thin limestone interbeds near the middle and at the top of the unit (Bannatyne, 1975). A corehole log and natural gamma geophysical log of the complete Fort Garry Member are shown in Figure 5 for a hole drilled in the northwestern part of the City of Winnipeg. A structure contour map showing the top of the member is given in Figure 6.

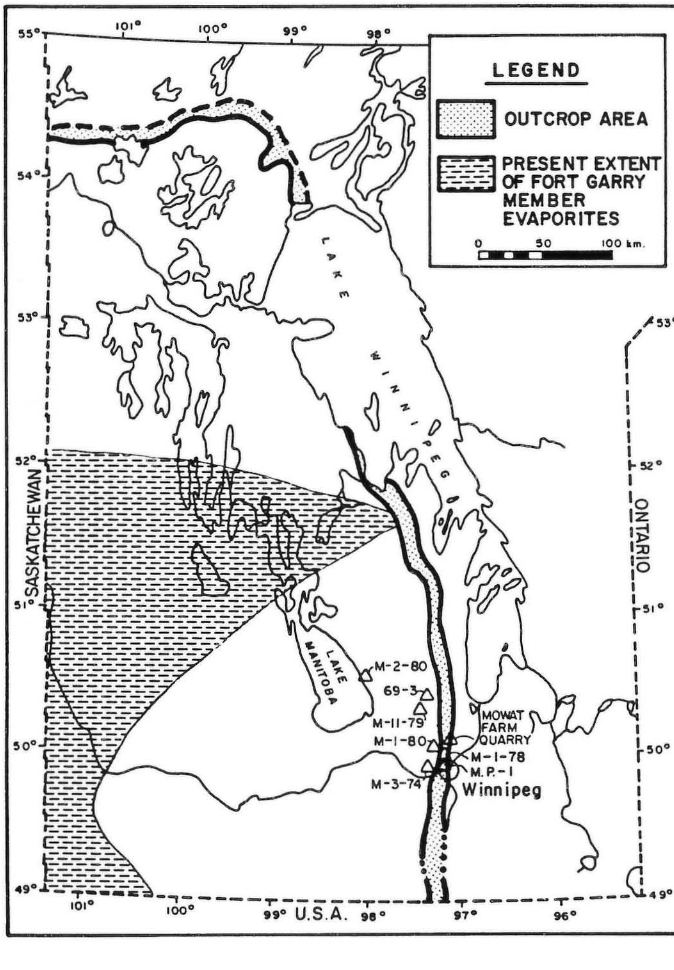

Figure 4: *The present extent of evaporite deposits in the upper Red River Formation (modified from Porter and Fuller, 1959, Fig. 11). Also shown is the location of the type outcrop section of the Fort Garry Member at the Mowat Farm quarry and the locations of core holes whose core was examined during this study.*

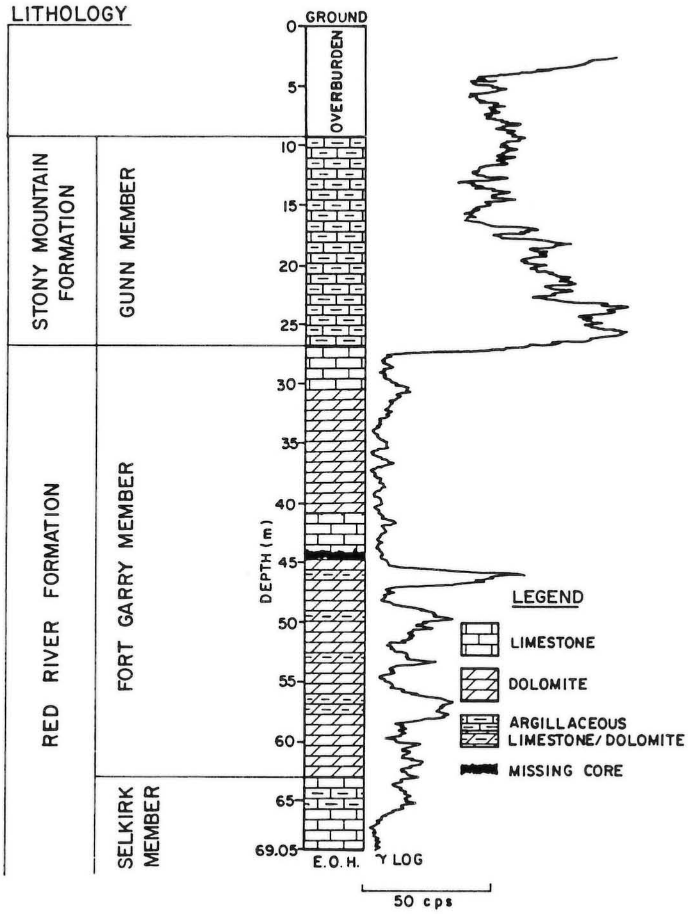

Figure 5: *Geological and natural gamma logs for corehole MP-1 located in northwestern Winnipeg showing the lithology of the Fort Garry Member and its relationship to overlying and underlying strata. Note the solution feature indicated by the zone of lost core located directly above the uppermost prominent argillaceous marker horizon.*

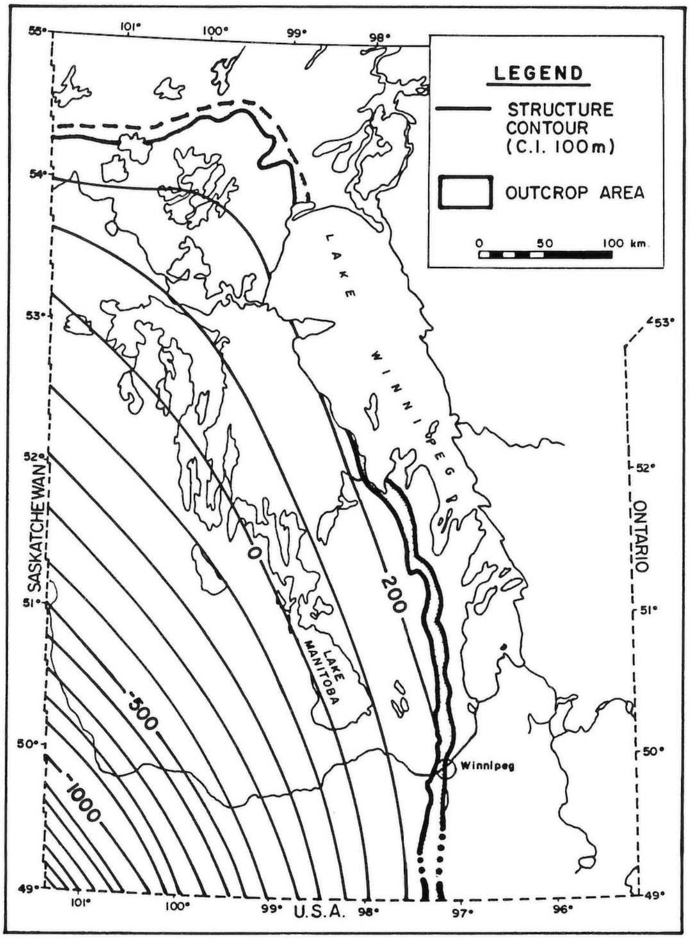

Figure 6: *Structure contour map of the top of the Fort Garry Member. (Modified from McCabe, 1972).*

HYDROGEOLOGY

Over the past decade, awareness of the large scale continuity of certain permeable features in the carbonate aquifer system has increased as a result of groundwater development in south-central Manitoba and test drilling programs undertaken by Manitoba Water Resources throughout the eastern portions of the sedimentary basin. Natural gamma geophysical logging of selected wells has greatly assisted in placing permeable zones into a stratigraphic framework. Caliper logging of these holes has also been very useful in identifying fractures. This is particularly the case in deep holes where increases in well yield while drilling with air-rotary methods are often difficult to identify when upper zones are producing considerable rates of flow.

Enhanced permeability in the Fort Garry Member of the Red River Formation was initially recognized in the western City of Winnipeg area where considerable groundwater development has taken place for heating and air conditioning purposes since the early 1980's (Render, 1983). Examination of water well drillers' logs has subsequently shown that this stratigraphic interval has persistent enhanced permeability throughout the eastern outcrop area of the carbonate rock aquifer system from the International Boundary northward to at least the upper basin of Lake Manitoba. Little information is available north of 52° latitude. One test hole located just south of Grand Rapids (Figure 1) produced substantial amounts of water from the Fort Garry Member and cores from a number of holes drilled for mineral exploration north of Cedar Lake show intervals of intense weathering and lost core from this Member (R. Bezys, personal communication). Recently, exploration work carried out as part of a large hydroelectric development on the Nelson River in northern Manitoba has found high permeabilities and apparent solution features in Fort Garry equivalent beds in the Hudson Bay Lowlands (R. Bezys, personal communication).

At greater depths, daily work sheets for more than half of 24 oil exploration wells located in the western part of the outcrop area and eastern part of the subcrop area indicate lost circulation, the use of circulation restoring mud additives or strongly "blowing" drill stem tests in the Fort Garry Member, indicating highly permeable conditions. In contrast, only two of 52 soil exploration wells drilled through the Fort Garry member in the western part of the subcrop area reported similar indications of high permeability in this interval.

The only known outcrop of the Fort Garry Member, south of Sylvan in southern Manitoba, occurs in the Mowat Farm quarry approximately 15 km north of Winnipeg (Fig. 4) in which approximately 7.15 m of the middle part of the member has been exposed (McCabe and Bannatyne, 1970; Elias *et al.*, 1988). The outcrop consists of approximately 2.5 metres of massive pale yellowish brown cherty dolomite overlying sublitho- graphic dolomite containing two thin, but pronounced, red shaly beds (McCabe and Barchyn, 1982). The upper cherty dolomite is sparsely fractured although it does contain a poorly interconnected vugular porosity. The underlying sublithographic dolomite is thinly bedded with bedding plane partings locally up to a centimetre in width. Bedding plane partings are interconnected by a network of subvertical fractures (Fig. 7). No significant solution features were observed in the pit. However, McCabe and Barchyn (1982) note that the prominent upper red shaly bed is overlain by "...minor structural undulation and associated microfaulting and brecciation..." which they interpret to be a result of solution and removal of evaporites from this horizon. Elias *et al.* (1988) have shown, on the basis of paleontological information, that this section corresponds to the upper Lake Alma and lower Coronach Members of the Herald Formation in Saskatchewan (Kendall, 1976), including the stratigraphic interval normally occupied by the Lake Alma anhydrite (immediately below the prominent red marker shale shown as interval II in Fig. 7). Elias *et al.* (1988) appear to accept the explanation of McCabe and Barchyn (1982) that the Lake Alma evaporite was deposited in this sequence but was later removed by solution.

Cores of complete or nearly complete sections of the Fort Garry Member were examined from seven core holes drilled in the southern half of the Paleozoic outcrop area (Fig. 4). In the cores the upper non-argillaceous part of the member (see Fig. 5) contained a vuggy porosity which did not appear to be well interconnected. Widely separated subhorizontal and subvertical fractures were observed which in places had slightly enhanced apertures as a result of weathering. Generally, fractures in the upper part of the member appeared to be tight, in some instances as a result of calcite infilling. Iron staining of fracture walls was extensive and, in places, the rock matrix showed slight to moderate weathering. A few zones of lost core were noted, perhaps indicating intense local solutioning.

The argillaceous middle part of the Fort Garry Member was characterized by frequent bedding plane partings and occasional zones of missing core or rubble, some of which may have been due to the effects of drilling in relatively soft thin-bedded rocks. Other rubbly zones appeared intensely solutioned and in one corehole (M.P.-1) a zone of missing core can be correlated to an interval of high permeability in a water well drilled approximately 3 m away. The lower middle and lower part of the member below the distinct argillaceous marker horizon seen on natural gamma logs contained few fractures. Those fractures which were observed were subvertical and appeared tight and unweathered or were filled with secondary calcite. No significant intergranular permeability was apparent.

Water well drilling records indicate that, where significant groundwater production has been obtained from the Fort Garry Member, groundwater is produced from one or more discrete zones which, on the basis of drilling response, range from a few centimetres to a metre or more in thickness. Drilling experience in Manitoba has shown that these significant water producing zones in the carbonate rock aquifer system correlate well with borehole enlargements detected with a mechanical 3-arm caliper device used in borehole geophysical logging by Manitoba Water Resources. Comparison of caliper responses with drill core in several holes has shown that the caliper tool rarely

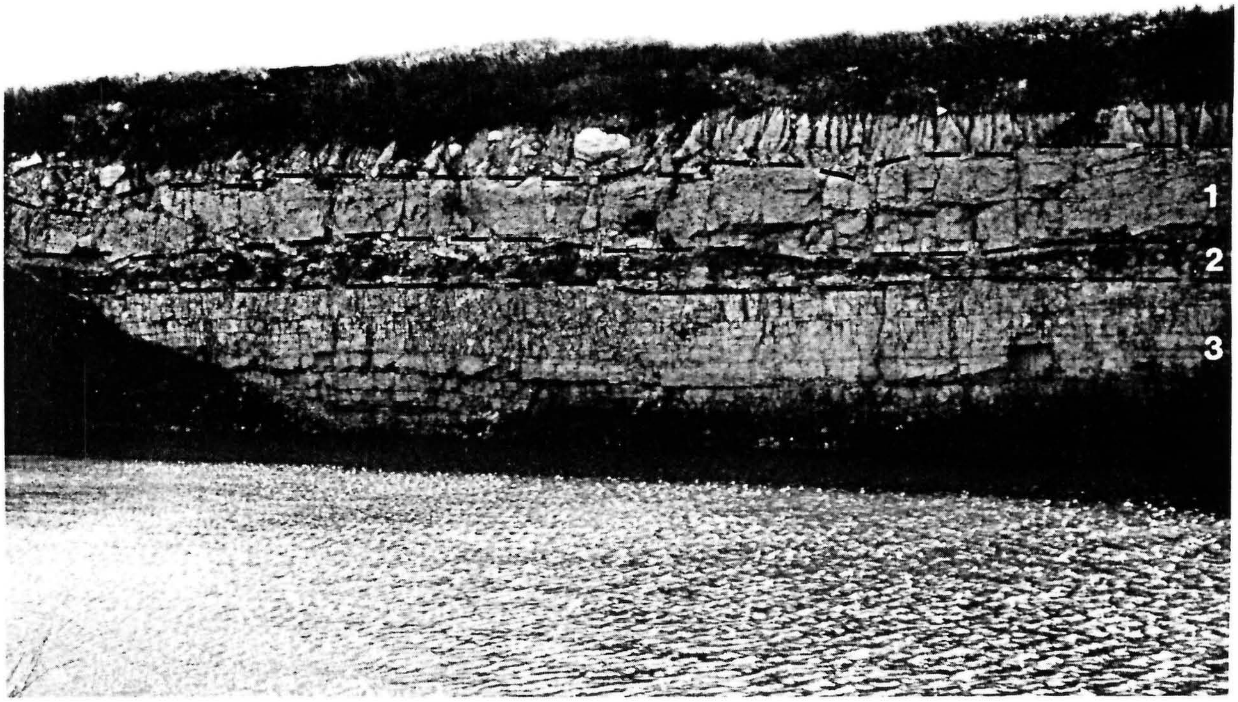

Figure 7: *Photograph of the middle Fort Garry Member exposed in the Mowat Farm quarry. Approximately 2 m of massive cherty dolomite (1) overlies 0.7 m of red argillaceous dolomite and shale (2) which is underlain by thinly bedded sublithographic dolomite (3). The Lake Alma anhydrite is found immediately beneath the argillaceous horizon in Saskatchewan. Minor structural undulation, micro-faulting and brecciation in the sediments overlying this interval in the quarry exposure are interpreted as disturbances resulting from solution of the anhydrite.*

shows a response to individual fractures but does respond to zones of rock "rubble", zones of missing core and zones showing extensive fracturing or solution weathering. As discussed above, these features will all be termed "fractures".

A stratigraphic cross-section running approximately north-south along the western edge of the outcrop area of the Fort Garry Member was constructed from water well and test hole information on file with Manitoba Water Resources. The cross-section, shown in Figure 9, runs for a north-south distance of approximately 200 km. Since the member was intersected at different depths in each hole, the cross-section was constructed using the top of the Red River Formation as the datum. The results of pumping tests on the Fort Garry Member and natural gamma and caliper geophysical logs are also shown where they are available. The well and test hole results shown in this cross-section are representative of results on file for a large number of wells completed in or through the upper Red River Formation in the outcrop area of the carbonate aquifer system in Manitoba.

The typical pattern of fracturing found in the upper Red River Formation is shown by the caliper logs of the holes used to construct the cross-section shown in Figure 8. Numerous borehole enlargements indicating water producing fractures are found throughout the Fort Garry Member and in some cases extend into the upper part of the Selkirk Member. Caliper responses range from individual deflections a few tens of centimetres thick to zones spanning several metres and including many individual fractures. Bit drops of 15 cm and occasionally much more have been noted while drilling through features showing responses similar to the more pronounced caliper responses seen in Figure 8. The degree of openness of some of these features can also be appreciated by considering that the fractured zones of the Fort Garry Member "thieved" as much as 6 cm of cuttings while drilling a deep waste disposal well about 15 km northwest of Winnipeg.

Where holes have been extended below the upper part of the Selkirk Member, caliper responses typically become much more widely spaced and less pronounced. The Selkirk, Cat Head and Dog Head Members, where encountered below the zone of enhanced permeability near the bedrock surface, have been found to be to be poorly permeable in many parts of southern Manitoba (Render, 1970; Betcher, 1984) although locally this interval does form a significant aquifer.

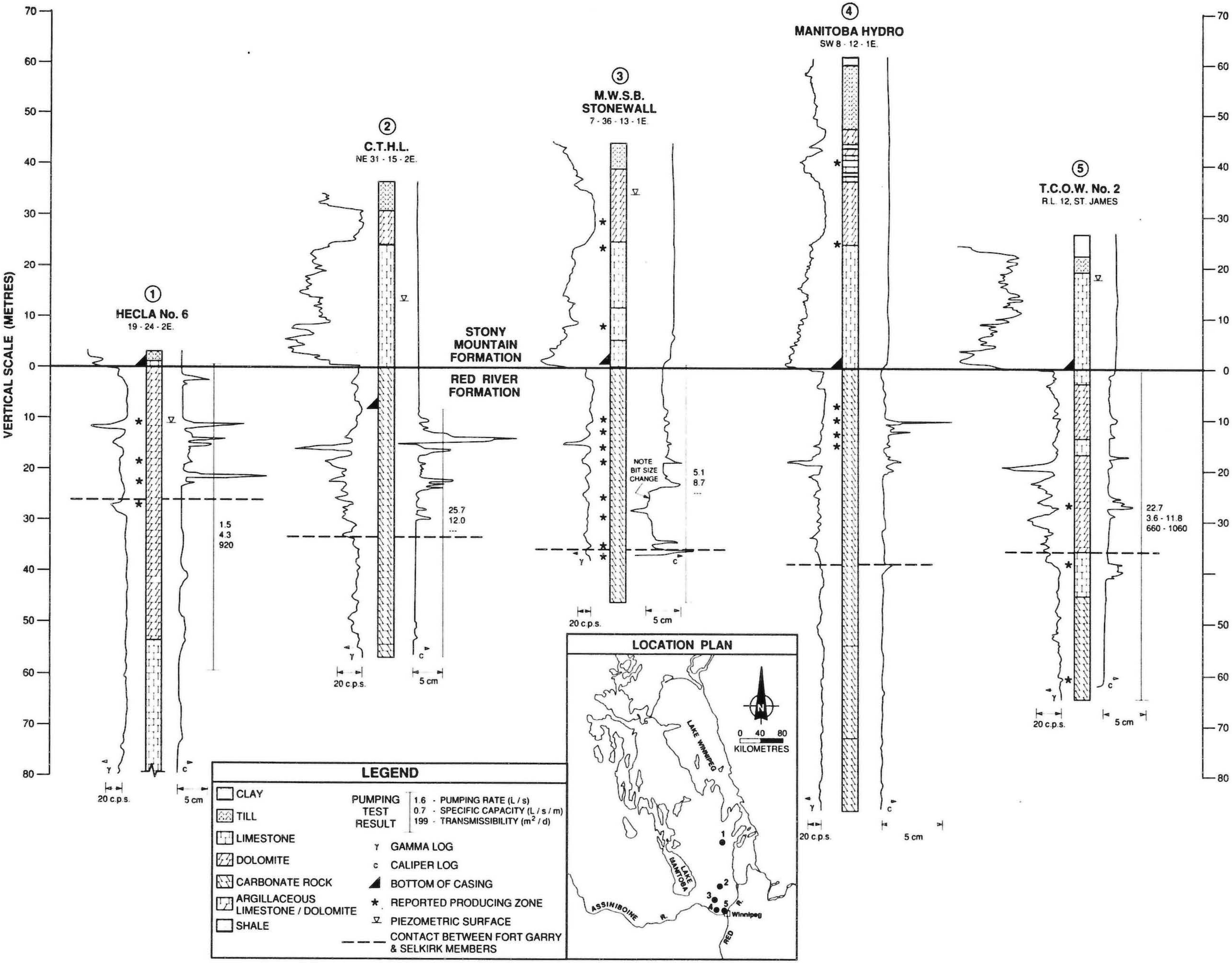

Figure 8: Hydrogeologic section stretching approximately 200 km north-south through southern and central Manitoba. Zero reference elevation is the top of the Red River Formation encountered in each well.

PUMPING TEST RESULTS

Pumping test information is available in Manitoba Water Resources Branch files for 23 wells completed in the Fort Garry Member. Only a few of these tests included observation wells and many of the tests were conducted in a less than ideal manner. A number of the wells were completed only through the upper part of the fractured interval of the member. Nonetheless the results that are available do indicate the yield which can be expected from this aquifer and provide an indication of the range of transmissibility.

Specific capacity values for these pumping tests are shown in histogram form in Figure 9. Where data were available, specific capacities were calculated after 60 minutes of pumping. Values ranged from 0.12 to 55.5 L/s/m, averaging 12.8 L/s/m. Well yields range from approximately 1 L/s to more than 100 L/s with most wells being capable of producing 20 L/s or more. Transmissibilities have been calculated from 16 pumping tests, most being single well tests, using Jacob's approximation (Cooper and Jacob, 1946). Transmissibility values ranged from 1.0×10^2 to 6.2×10^3 m^2/d with a median value of 9.1×10^2 m^2/d.

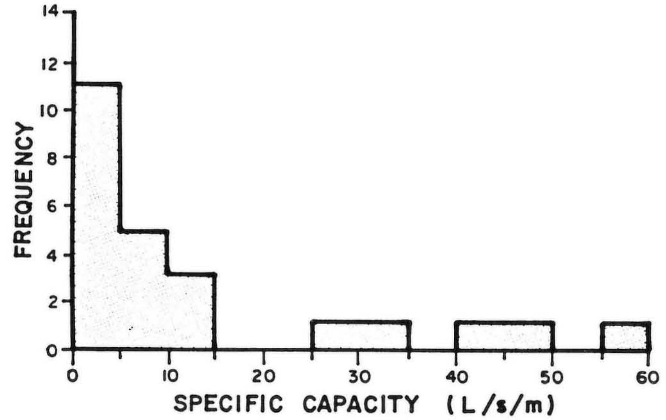

Figure 9: Histogram of specific capacity values for wells completed in the Fort Garry aquifer.

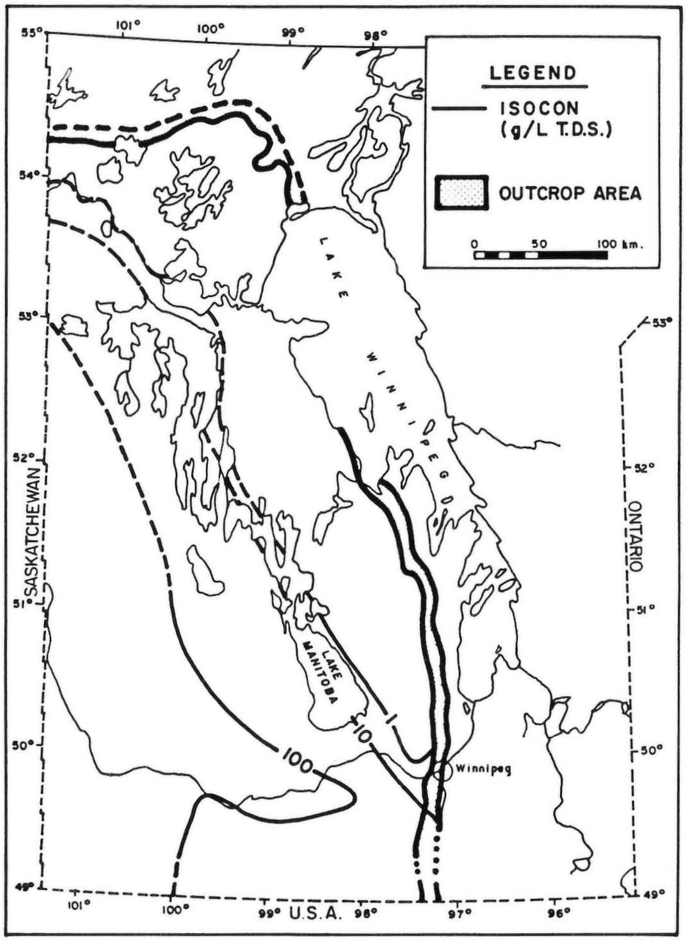

Figure 10: Distribution of total dissolved solids in the Fort Garry aquifer. Note the logarithmic contour interval.

GROUNDWATER QUALITY

The regional distribution of total dissolved solids (TDS) in the Fort Garry aquifer is shown on Figure 10. This map was constructed using water quality data on file with Manitoba Water Resources and analyses of 22 formation water samples collected during drill stem tests in oil exploration wells (Anonymous, 1984). The drill stem test results are generally from the deeper parts of the sedimentary basin lying west and south of lakes Manitoba and Winnipegosis and include results from all tested intervals of the Red River Formation. In this deep part of the basin, vertical water quality stratification in the Formation has been assumed to be relatively unimportant. Groundwaters in the Fort Garry aquifer are fresh (TDS <1000 mg/L) throughout most of the area lying to the north and east of the Saskatchewan River and lakes Winnipegosis and Manitoba, extending south to within approximately 15 km of the Assiniboine River and the City of Winnipeg. Fresh groundwaters are generally a Mg-Ca-HCO_3 type reflecting geochemical development in a carbonate terrain. A full discussion of the geochemistry of these groundwaters will be presented in a future paper.

Groundwater quality declines rapidly to the south and west of the fresh water zone. A transition zone of Na-Cl-SO_4 brackish groundwater approximately 25 to 50 km wide in southern Manitoba separates fresh groundwaters from Na-Cl type saline groundwaters and brines found farther to the south and west. Total dissolved solids contents exceed 250,000 mg/L near the Saskatchewan border. These saline waters and brines form the northeastern extent of a large body of highly saline waters occupying the central portion of the Williston Basin through parts of Saskatchewan, North Dakota, South Dakota and Montana (Downey, 1984).

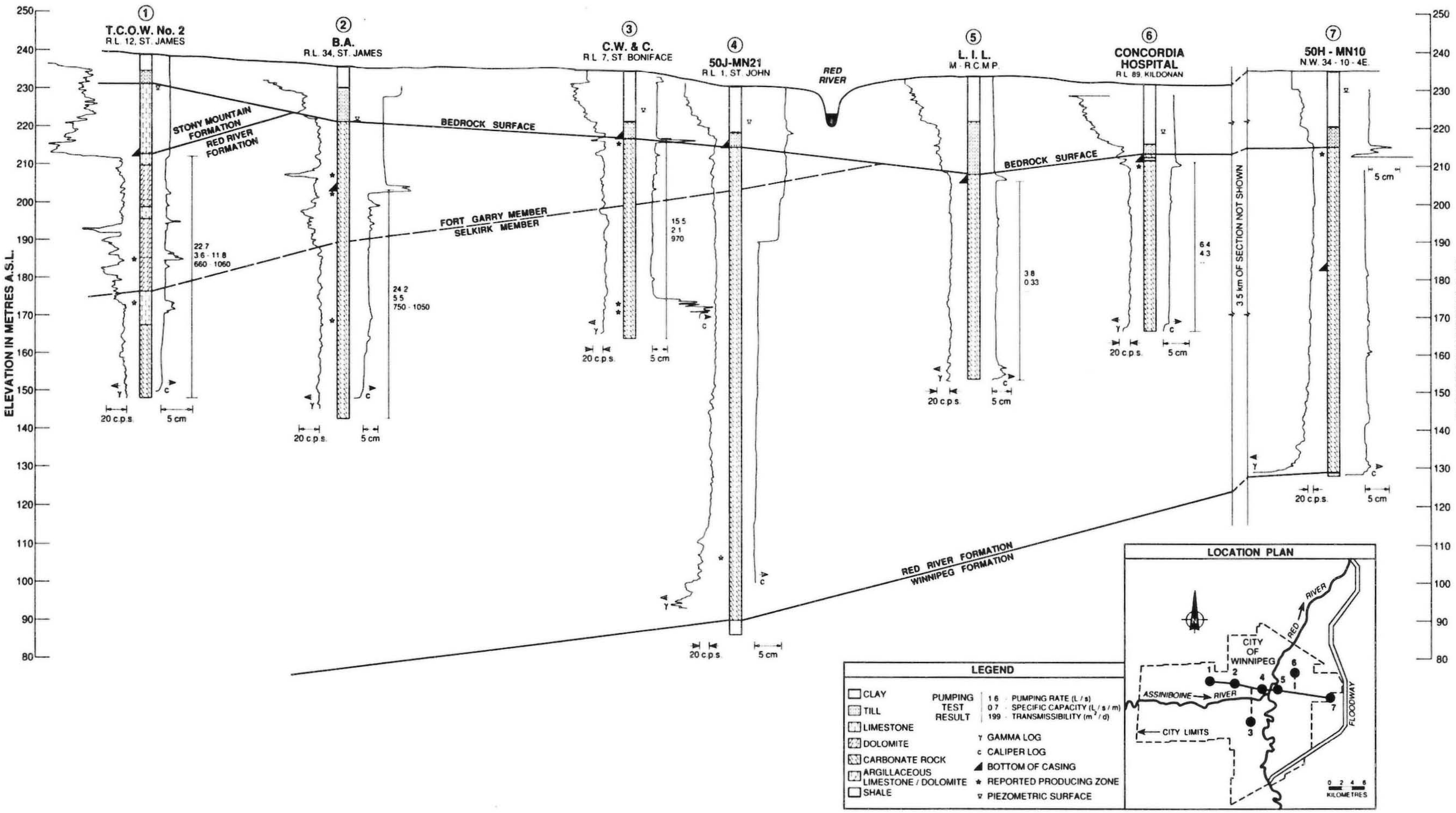

Figure 11: Hydrogeologic cross-section running approximately up-dip through City of Winnipeg. See text for discussion.

INFLUENCE ON CITY OF WINNIPEG HYDROGEOLOGY

Render (1970) discussed the hydrogeology of the carbonate aquifer system in the City of Winnipeg area of southern Manitoba. This aquifer system supplies approximately 1.4 X 10^{10} litres of water per year for consumptive and thermal use within the city, making it one of the largest water supply aquifers in Canada. Render recognized "upper" and "lower" aquifers within the carbonate rock system. The upper aquifer occurs principally within the top 7.5 m of bedrock and forms the major zone of permeability in the carbonate rock. The lower aquifer is formed by a zone of moderate fracture permeability in the bottom 15 m of carbonate rock overlying the Winnipeg Formation. The two aquifers were found to be separated by a thick interval of carbonate rock having a very low fracture frequency.

Recognition of the Fort Garry aquifer modifies the model of permeability distribution presented by Render (1970) for the upper part of the carbonate aquifer system. Figure 11 presents a hydrogeological cross-section running approximately east-west through the city, along the dip of the bedrock strata. West of Winnipeg the Fort Garry Member is overlain by the Stony Mountain Formation. The member rises updip towards the east and subcrops beneath overlying clay and till in the central and west-central parts of the City. East of the Red River the Fort Garry Member has been completely removed by erosion.

In the western part of Winnipeg, well logs and borehole geophysical logs show that groundwater supplies generally are obtained from the Fort Garry aquifer; the overlying Stony Mountain argillaceous limestones are generally poorly permeable or are unstable and are cased off. Well yields from the Fort Garry aquifer in this area tend to be relatively consistent from 10 to 20 L/s. Farther west, the upper dolomites of the Stony Mountain Formation form a local aquifer. Limited drilling below the Fort Garry Member indicates that the lower portions of the Red River Formation are poorly fractured and do not form a significant aquifer. In the west-central part of the city, groundwater supplies are also obtained primarily from the Fort Garry aquifer, including the upper part of the aquifer near the bedrock surface where permeability is often found to be enhanced (Render's upper aquifer). Many of the most productive wells in Winnipeg are located in this region. However, as the Fort Garry Member pinches out near the Red River, well yields become more variable and wells which do not encounter significant permeability in the upper part of the bedrock may be very poor producers. The permeability of the Red River Formation below the Fort Garry Member is generally very low (e.g. 5OJ-MN21, Fig. 11) although Render (1970) does indicate a "lower" aquifer near the base of the Formation. One significant exception is well C.W. & C. shown in Figure 11. This well encountered a highly weathered solution zone more than 5 m thick in the Selkirk Member about 25 m below the base of the Fort Garry Member.

East of the Red River the enhanced permeability associated with the Fort Garry Member is not present. In many wells the most significant zones of groundwater production are found in the upper few metres or tens of metres of the carbonate bedrock. Below this zone the rock tends to be relatively unfractured although subvertical solution features of limited areal extent have been intersected in a number of wells and indicate that significant permeability may extend downward for several tens of metres in some areas.

DISCUSSION

We have shown that the upper part of the Red River Formation, roughly correlating with the Fort Garry Member, forms a persistent interval of enhanced permeability throughout a remarkably large area within southern and central Manitoba. Examination of cores and outcrop indicates that the intrinsic permeability of this unit is very small. As well, vertical fractures are uncommon and frequently sealed with calcite infilling. The major permeability of the unit is found within discrete intervals a few centimetres to several metres wide which are recognized as bit drops during drilling, as intervals of lost or highly weathered and fractured core or as borehole enlargements on caliper logs. These zones are thought to be oriented subhorizontally since most vertically drilled wells penetrating the unit have intersected substantial permeabilities.

The pattern of permeability distribution found in the Fort Garry Member is typical of carbonate rocks in which solution processes have been active (Lattman and Parizek, 1964; Ford and Ewers, 1978; Stringfield *et al.* 1979; James and Choquette, 1988; and many others). What is somewhat unusual, however, is the large areal extent over which solution-enhanced permeability has developed within this specific geological unit, particularly since this enhanced permeability is found not only near the present outcrop area of the Member but also where the Member is overlain by as much as several hundred metres of post-Ordovician sediments. This would indicate that either the dissolution process responsible for development of the enhanced permeability found in the unit occurred soon after deposition of the Fort Garry Member or that development of solution-enhanced permeability has been controlled by geological or structural conditions peculiar to the Member.

A paleontological study of the middle to upper part of the Fort Garry Member led Elias *et al.* (1988) to conclude that virtually all deposition occurred in subtidal environments with perhaps a period of emergence following deposition of evaporites. A depositional environment is thought to have persisted with only minor interruptions until the Late Silurian (Andrichuk, 1959). Although removal of evaporites deposited during high salinity periods of Fort Garry time could have begun as early as the return to normal marine salinity conditions, there is no evidence of widespread erosion during this time that could account for the development of the significant solution features observed in the member. In particular, intraformational breccias are found in the Fort Garry Member only in the outcrop area where anhydrites are absent but are not found in the Member in the subcrop area where anhydrite layers are present. This indicates that removal of the anhydrites and development of breccias occurred much later in the geological history of the basin.

Simpson *et al.* (1987) discussed a number of local and regional episodes of non-deposition and erosion which took place in southern Manitoba in post-Late Silurian time. The most significant events occurred from Upper Silurian until Middle Devonian, from Late Paleozoic to Early Mesozoic, from the Upper Jurassic to Lower Cretaceous and during the Cenozoic. These events have been responsible for removal of as much as several hundred metres of Paleozoic sediments and creation of the truncated Paleozoic surface seen in Figure 3. Evidence for extensive development of karst features during the Late Paleozoic to Early Mesozoic and Upper Jurassic to Lower Cretaceous erosional episodes, including sinkholes, solution caverns and channels, is found in many parts of the Paleozoic rock outcrop area in southern Manitoba (Grice, 1964; Manitoba Mineral Resources Division, 1979; Simpson *et al.* 1987). Paleo-karst features have been found extending into the Fort Garry Member and include channels infilled with Jurassic and Cretaceous sediments (Bannatyne, 1970; Manitoba Mineral Resources Division, 1979) and sinkholes infilled with Lower Cretaceous (?) sediments (Rutulis, 1981; Betcher, 1983).

It is postulated that development of widespread solutional feature permeability occurred in the Fort Garry Member during these erosional episodes, beginning perhaps as early as the Late Silurian but more likely, during Late Paleozoic uplift and erosion. Marine withdrawal would have allowed active fresh groundwater flow systems to develop in the bedrock. Dissolution and removal of the widely distributed anhydrite beds in the Fort Garry Member would have created preferred sub- horizontal pathways for groundwater movement and further development of permeable solution features. Shaly horizons within the Member may also have enhanced the sub-horizontal flow of groundwaters by directing water movement parallel to the dip of these beds (Ford and Ewers, 1978). This process would have led to development of enhanced permeability in the Fort Garry Member on a regional scale, consistent with the widespread distribution of high permeability found in the Member in Manitoba today.

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REFERENCES

Andrichuk, J.M.

1959: Ordovician and Silurian stratigraphy and sedimentation in southern Manitoba, Canada; Bulletin of the American Association of Petroleum Geologists, Volume 43, Number 10, p. 2333-2398.

Anonymous

1984: Lower Paleozoic formation water analyses Bakken to Precambrian; Unpublished report, Manitoba Energy and Mines, Winnipeg, Manitoba.

Bannatyne, B.B.

1970: The clays and shales of Manitoba; Manitoba Department of Mines and Natural Resources, Mines Branch, Publication 67-1.

Bannatyne, B.B.

1975: High-calcium limestone deposits of Manitoba; Manitoba Department of Mines, Resources and Environmental Management, Mineral Resources Division, Publication 75-1.

Betcher, R.N.

1983: Groundwater availability map series - Hecla area (62P); Manitoba Natural Resources, Hydrotechnical Services.

Betcher, R.N.

1984: The potential for saline waste water disposal into deep geologic formations, Dorsey Station, Manitoba; Manitoba Department of Natural Resources, Water Resources Branch.

Betcher, R.N.

1986: Regional hydrogeology of the Winnipeg Formation in Manitoba; In Proceedings of the Third Canadian Hydrogeology Conference, Saskatchewan, Saskatchewan, April 20-23, 1986.

Cooper, H.H., Jr. and Jacob, C.E.

1946: A generalized graphical method for evaluating formation constants and summarizing well field history; Transactions of the American Geophysical Union, Volume 27, p. 526-534.

Downey, J.S.

1984: Geohydrology of the Madison and associated aquifers in parts of Montana, North Dakota, South Dakota, and Wyoming; United States Geological Survey Professional Paper 1273-G.

Elias, R.J.

1988: Paleontology of the type section, Fort Garry Member, Red River Formation (Upper Ordovician), southern Manitoba; New Mexico Bureau of Mines Mineral Resources, Memoir 44, p. 341-359.

Ford, D.C. and Ewers, R.O.

1978: The development of limestone cave systems in the dimensions of length and depth; Canadian Journal of Earth Sciences, Volume 15, p. 1783-1798.

Grice, R.H.

1964: Hydrogeology at a hydroelectric installation on Paleozoic dolomites at Grand Rapids, Manitoba; Unpublished Ph.D. Thesis, University of Illinois, Urbana, Illinois.

James, N.P. and Choquette, P.W. (editors)

1988: Paleokarst. Springer-Verlag, New York.

Kendall, A.C.

1976: The Ordovician carbonate succession (Bighorn Group) of southeastern Saskatchewan; Department of Mineral Resources, Saskatchewan Geological Survey, Sedimentary Geology Division, Report Number 180.

Lattman, L.H. and Parizek, R.R.

1964: Relationship between fracture traces and the occurrence of ground water in carbonate rocks. Journal of Hydrology, Volume 2, pages 73-91; Manitoba Mineral Resources Division, 1979. Geological map of Manitoba, scale 1:1,000,000, Map 79-2.

McCabe, H.R.

1971: Stratigraphy of Manitoba, an introduction and review; In Geoscience studies in Manitoba, edited by A. C. Turnock, Geological Association of Canada Special Paper 9, p. 167-187.

McCabe, H.R. and Bannatyne, B.B.

1970: Lake St. Martin crypto-explosion crater and geology of the surrounding area. Manitoba; Department of Mines and Natural Resources, Geological Paper 3/70.

McCabe, H.R. and D.Barchyn

1982: Paleozoic stratigraphy of southwestern Manitoba; Field trip guidebook, trip 10, Geological Association of Canada and Mineralogical Association of Canada joint annual meeting, Winnipeg, Manitoba, 1982.

Porter, J.W. and Fuller, J.G.C.M.

1959: Lower Paleozoic rocks of northern Williston Basin and adjacent areas; Bulletin of the American Association of Petroleum Geologists, Volume 43, Number 1, p. 124-189.

Render, F.W.

1970: Geohydrology of the metropolitan Winnipeg area as related to groundwater supply and construction; Canadian Geotechnical Journal, Volume 7, p. 243-274.

Render, F.W.

1983: Hydrology; In Geological engineering maps and report for urban development of Winnipeg. Department of Geological Engineering, University of Manitoba, Winnipeg, Manitoba, p. 29-40.

Rutulis, M.

1981: Groundwater resources in the Cooks Creek Conservation District; Unpublished report, Manitoba Water Resources Branch, Winnipeg Manitoba.

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

1987: Subsurface disposal of wastes in Manitoba Part I: current status and potential of subsurface disposal of fluid industrial wastes in Manitoba; Manitoba Energy and Mines, Geological Paper GP 83-1.

Stringfield, V.T., Rapp, J.R. and Anders, R.B.

1979: Effects of karst and geologic structure on the circulation of water and permeability in carbonate aquifers; Journal of Hydrology, Volume 43, p. 313-332.

Trainor, F.W.

1973: Formation of joints in bedrock by moving glacial ice; Journal of Research of the United States Geological Survey, Volume 1, Number 2, p. 229-235.