HARDY LECTURE

GLACIAL GEOLOGY OF SOUTHERN SASKATCHEWAN

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Glacial Geology of Southern Saskatchewan

E.A. Christiansen

Glacial Geology of Southern Saskatchewan

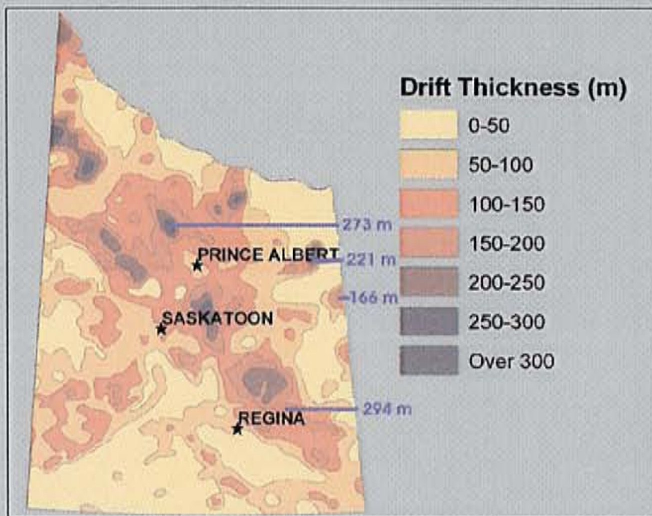
- Stratigraphy
- Geologic Processes
- Groundwater Occurrence

Glacial Geology of Southern Saskatchewan

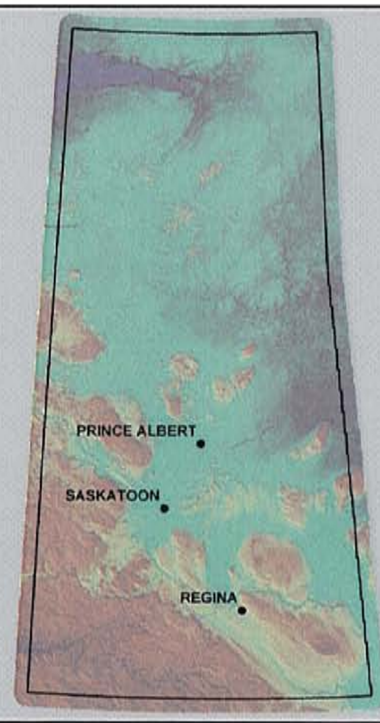
- **Stratigraphy**
  - Bedrock
  - Thickness of glacial deposits
  - Shuttle radar topography
  - Methodology of separating stratigraphic deposits
  - Source of tills
- Geologic Processes
- Groundwater Occurrence

Bedrock geology of Saskatchewan

Drift thickness



Shuttle radar topographic map



A formation is a sequence of:

1. Lower stratified deposits laid down during glacier advances
2. Basal and ablation melt out tills deposited directly during retreat of the glaciers
3. Upper stratified deposits laid down during retreat of the glaciers.

Unconformity

Formation	Upper stratified deposits	Fining upward	One Glaciation
	Basal and Ablation melt out tills	Nonsorted	
	Lower stratified deposits	Coarsening upward	

Unconformity

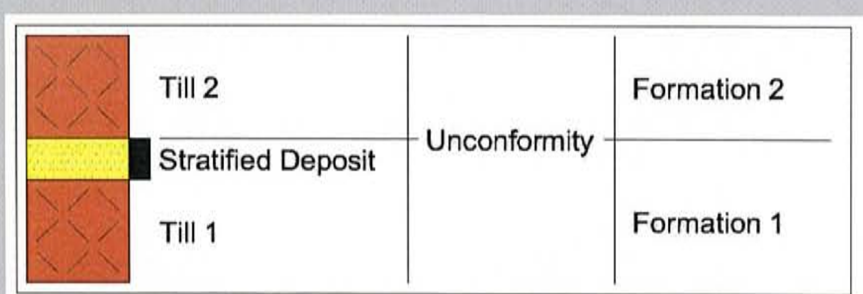
Unconformity

- An unconformity is a surface of erosion or nondeposition that represents a time gap in the geologic record

Oxidized zone

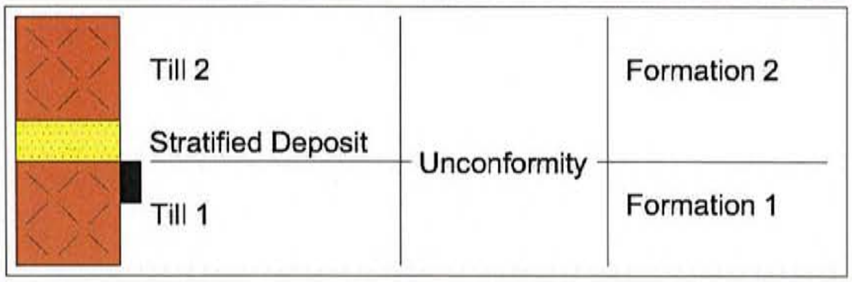
- An oxidized zone develops in the zone of aeration as a result of oxidation of gray ferrous iron to brown ferric iron. The top of an oxidized zone is an unconformity

Association of tills and stratified deposits



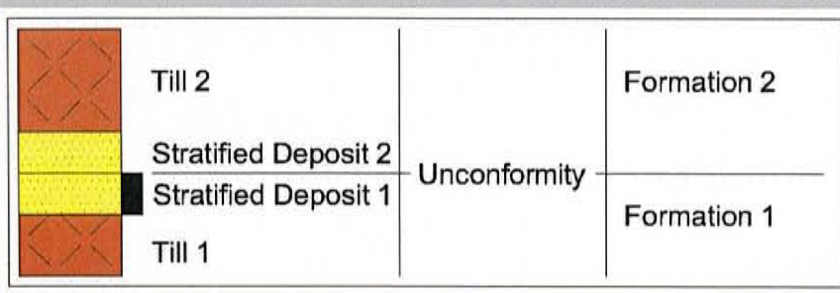
Stratified deposit associated with till 1

Association of tills and stratified deposits



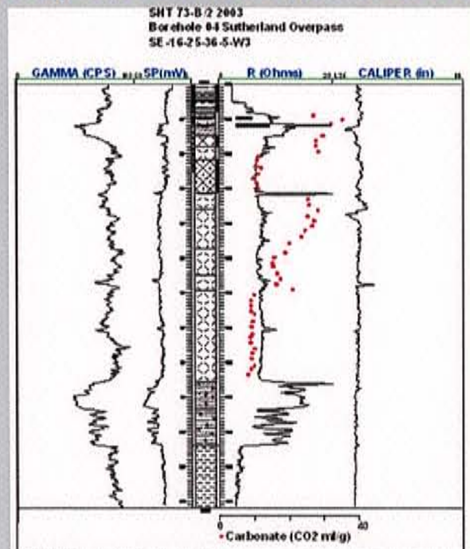
Stratified deposit associated with till 2

Association of tills and stratified deposits

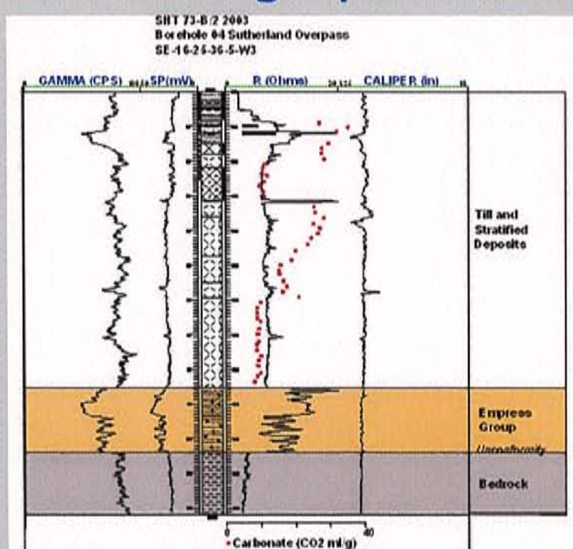


Stratified deposit 1 is associated with till 1 and stratified deposit 2 associated with till 2

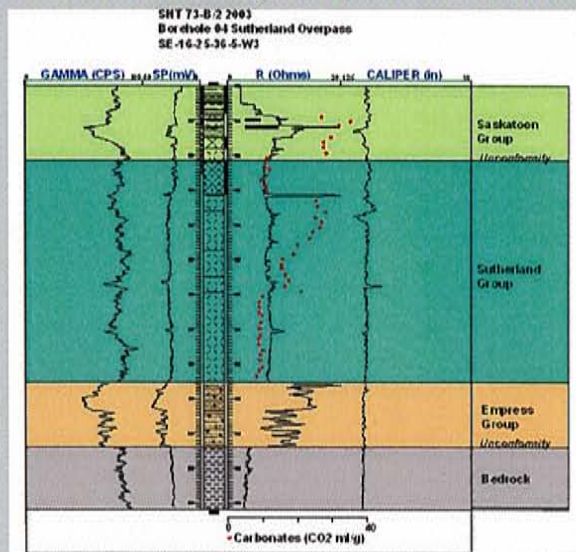
Stratigraphic interpretation



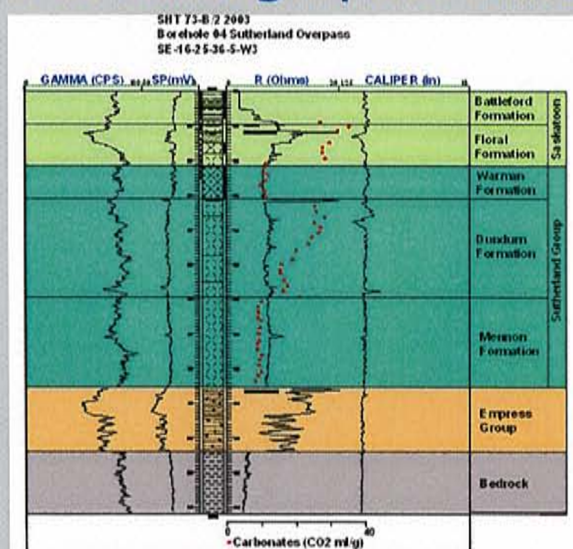
Phase 1 of stratigraphic units



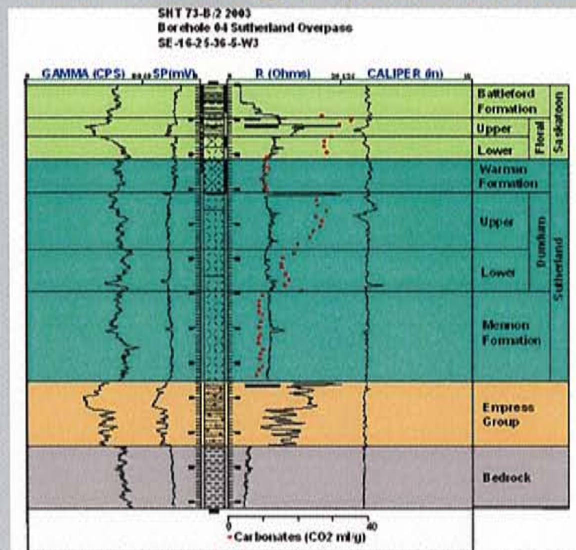
Phase 2 of stratigraphic units



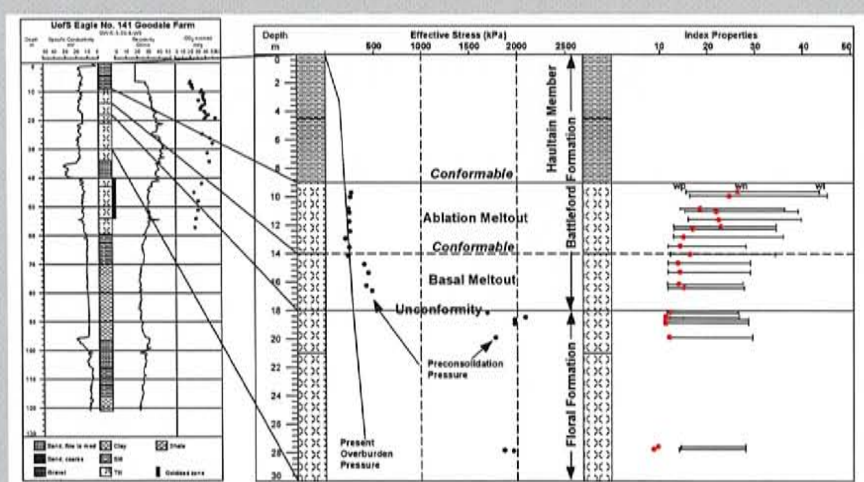
Phase 3 of stratigraphic units



Phase 4 of stratigraphic units

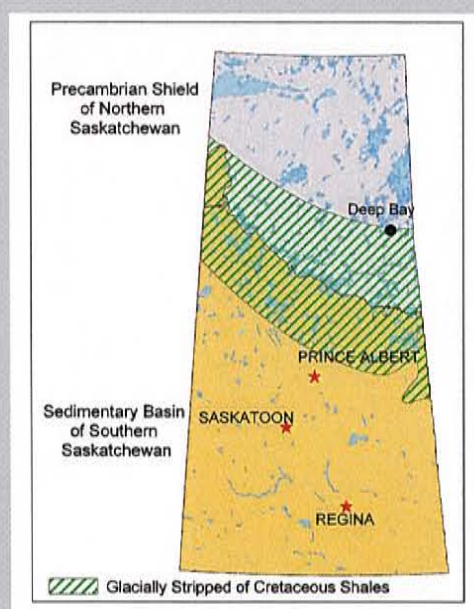


Preconsolidation pressures and index properties



Keewatin and Labrador ice centers

Progressive stripping to form tills



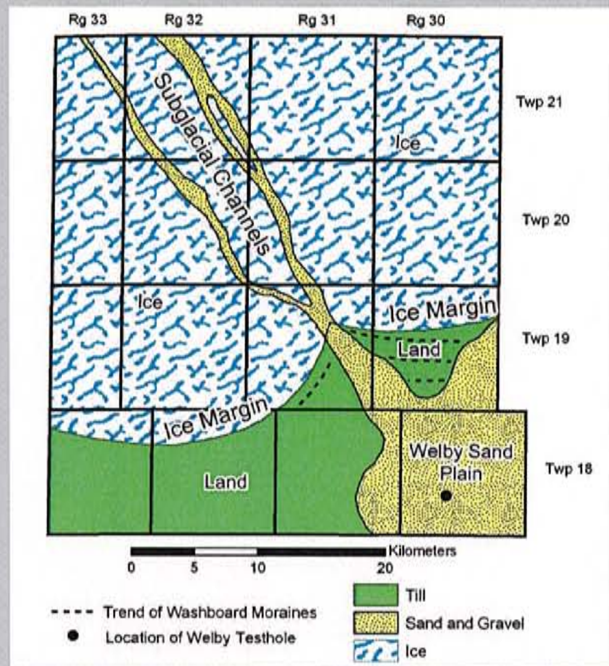
Glacial Geology of Southern Saskatchewan

- Stratigraphy
- **Geologic Processes**
  - Outwash
  - Inwash
  - Salt collapse
- Groundwater Occurrence

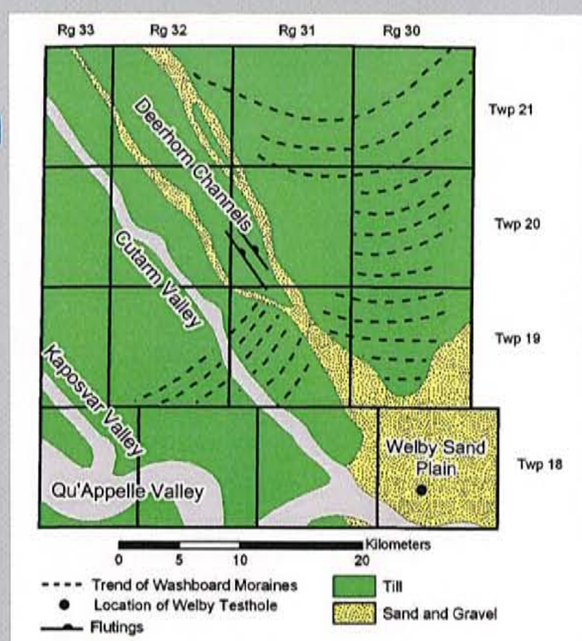
Outwash

- Outwash is chiefly sand and gravel "washed out" from a glacier by meltwater streams

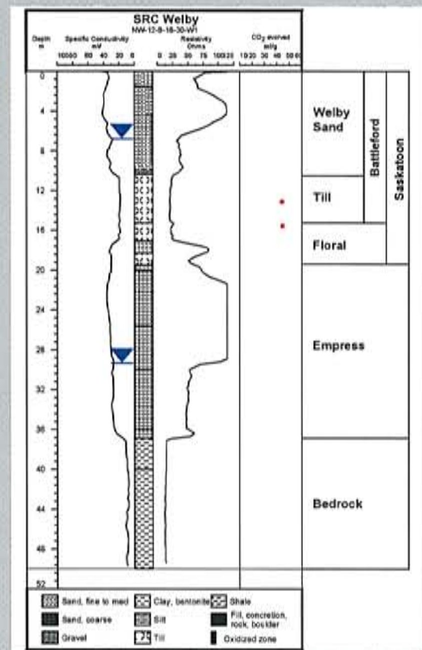
Welby sand plain - phase 1



Welby sand plain - phase 2



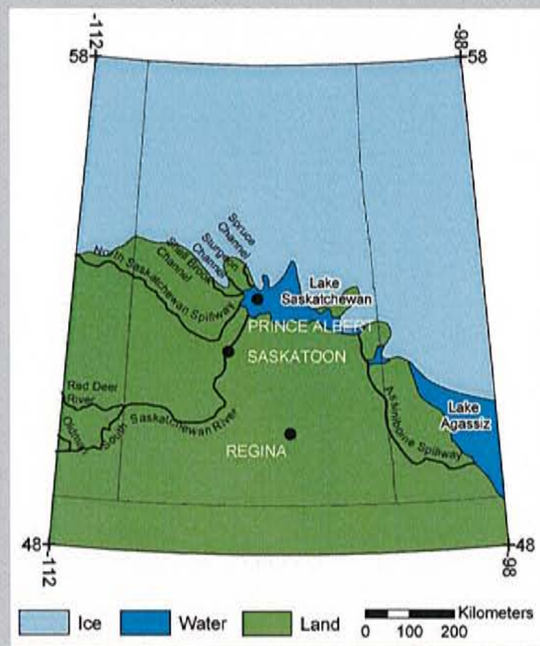
Welby sand plain



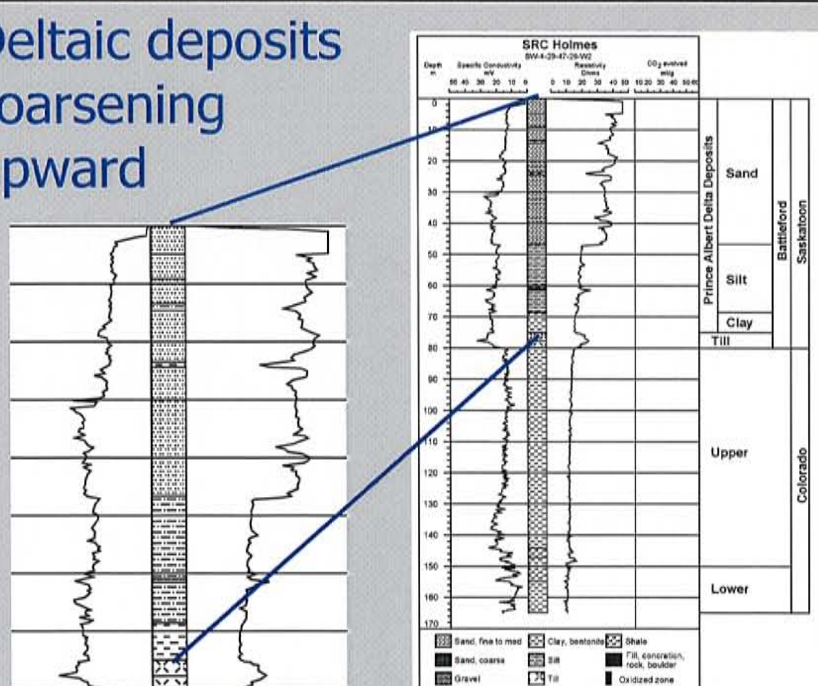
Inwash

- Inwash is deltaic sediments deposited in proglacial lakes by extraglacial and glacial streams

Prince Albert delta



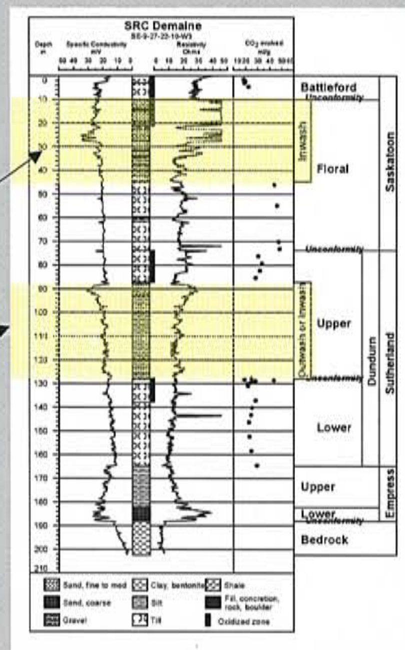
Deltaic deposits coarsening upward



Differentiation of outwash and inwash

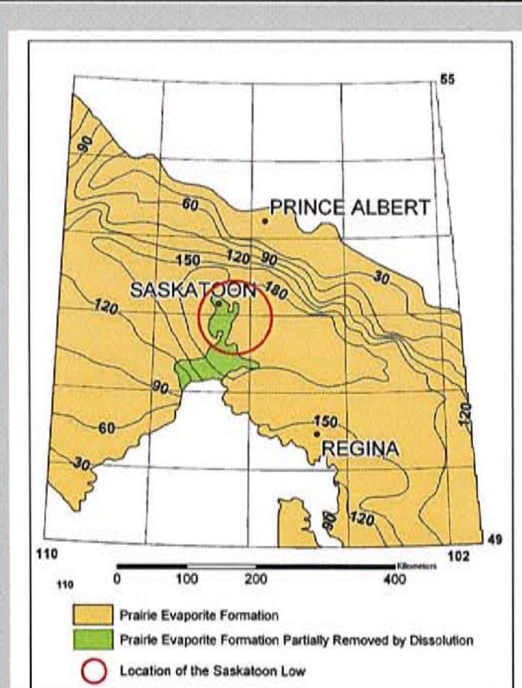
Inwash

Outwash or inwash

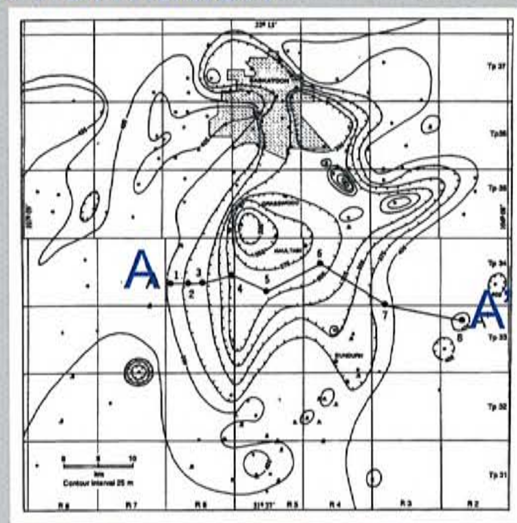


Salt Collapse

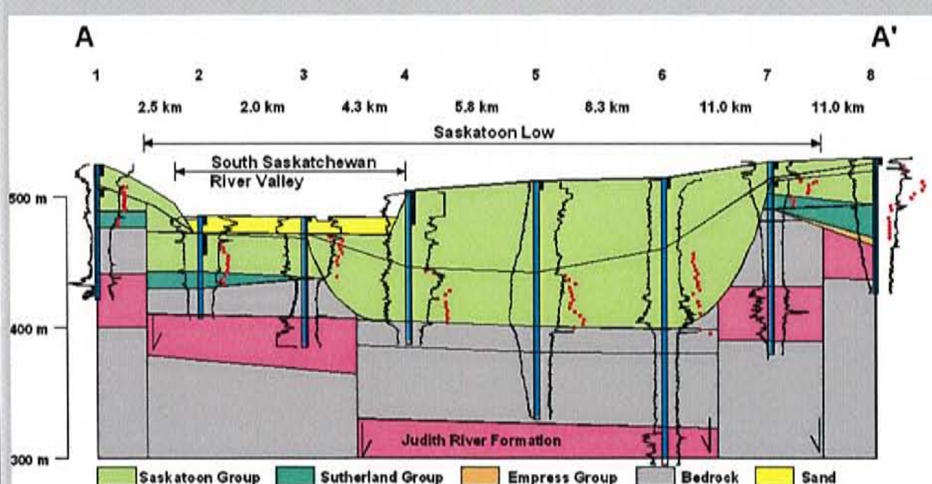
Isopach map of the Prairie Evaporite



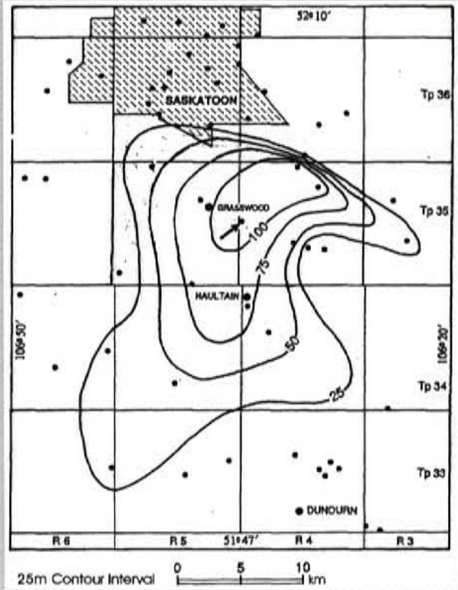
Structure contour map on top of the Lea Park Formation



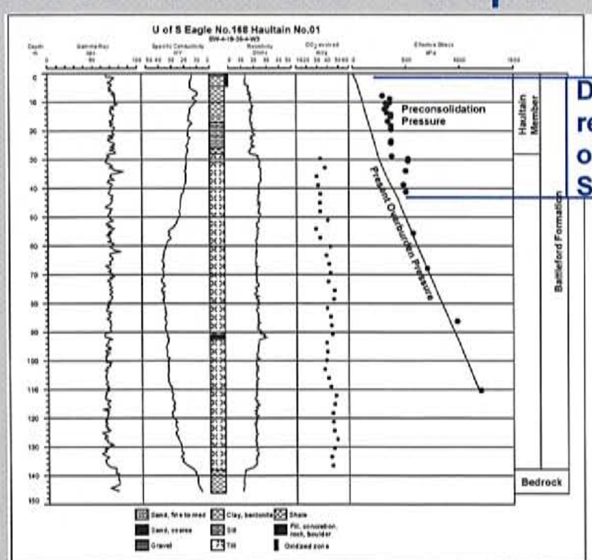
Cross Section across the Saskatoon Low



Isopach map of till of the Battleford Formation

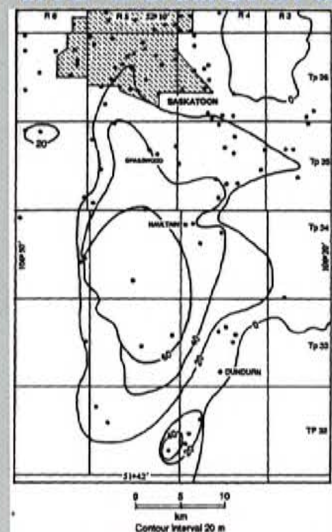


Effective stress – depth curve



Desiccation as a result of drainage of glacial Lake Saskatchewan

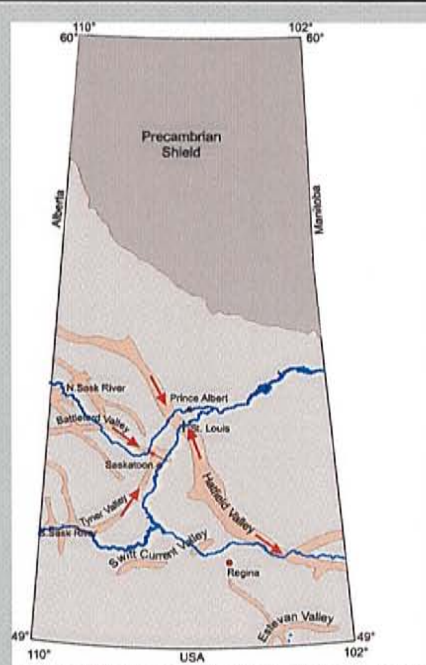
Isopach map of the Haultain Member of the Battleford Formation



Glacial Geology of Southern Saskatchewan

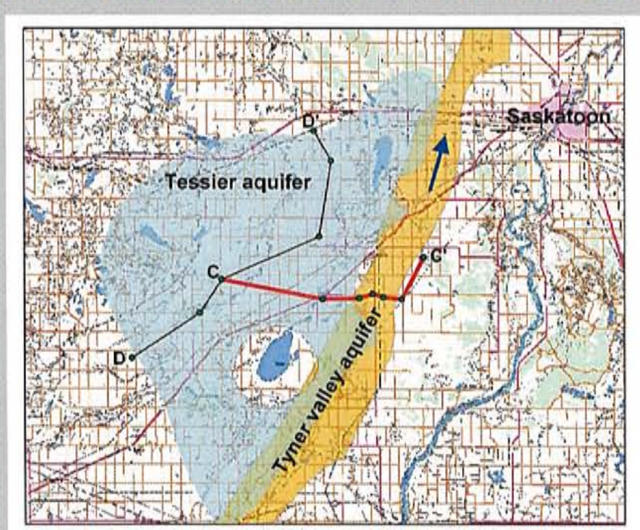
- Stratigraphy
- Geologic Processes
- **Groundwater Occurrence**
  - Major aquifers yielding potable water
  - Tessier and Tyner valley aquifers
  - Battleford valley and the Fielding and Dalmeny aquifers

Major bedrock valleys

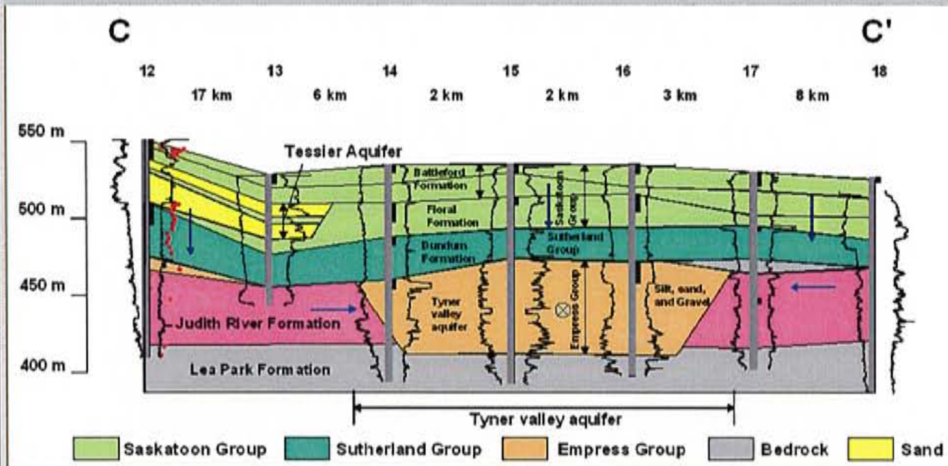


Major aquifers in Saskatchewan yielding potable water
(Source: H. Maathuis, Saskatchewan Research Council)

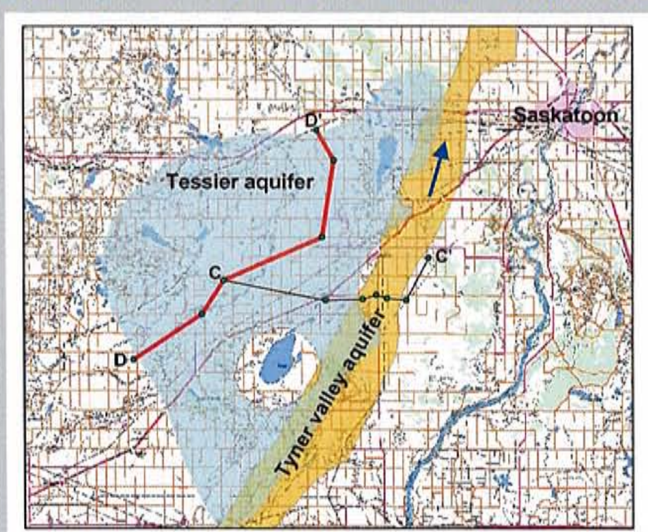
Tessier and Tyner valley aquifers



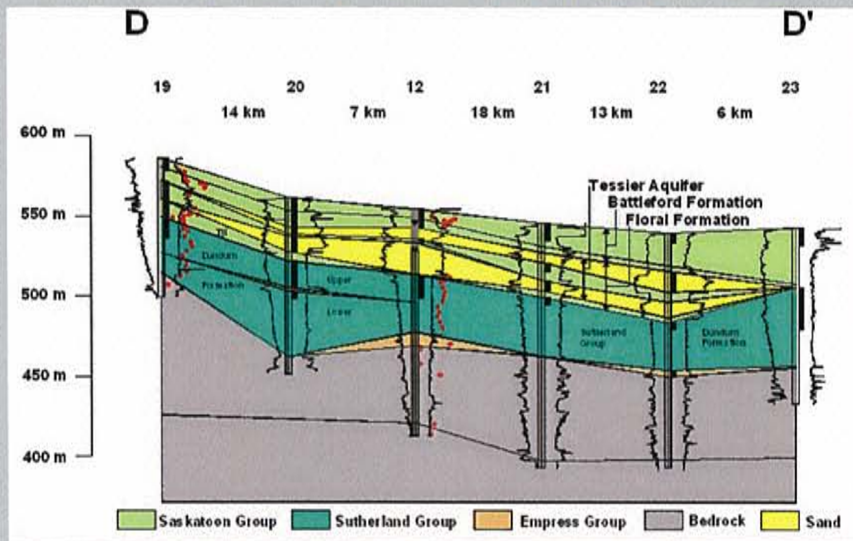
Tessier and Tyner valley aquifers



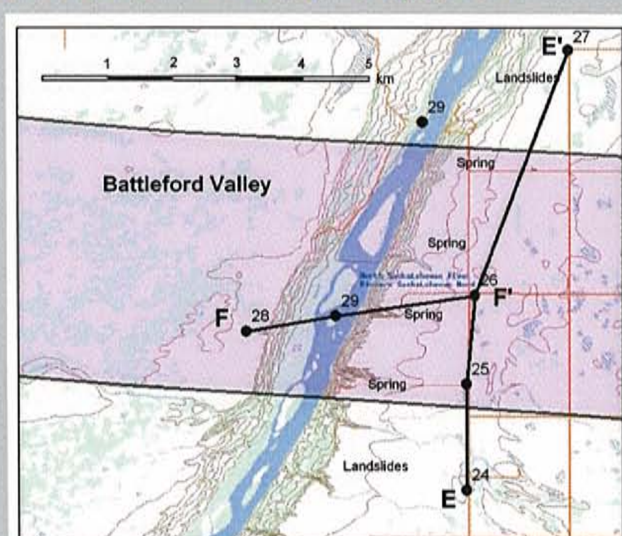
Tessier and Tyner valley aquifers



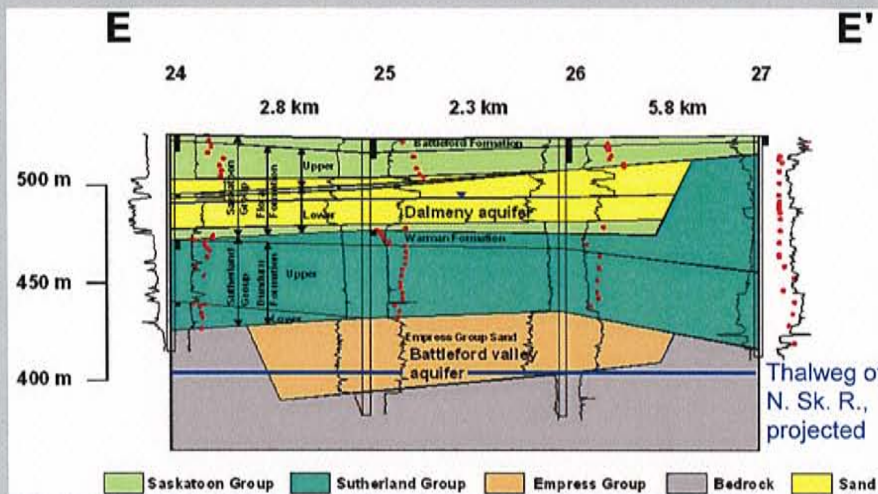
Tessier and Tyner valley aquifers



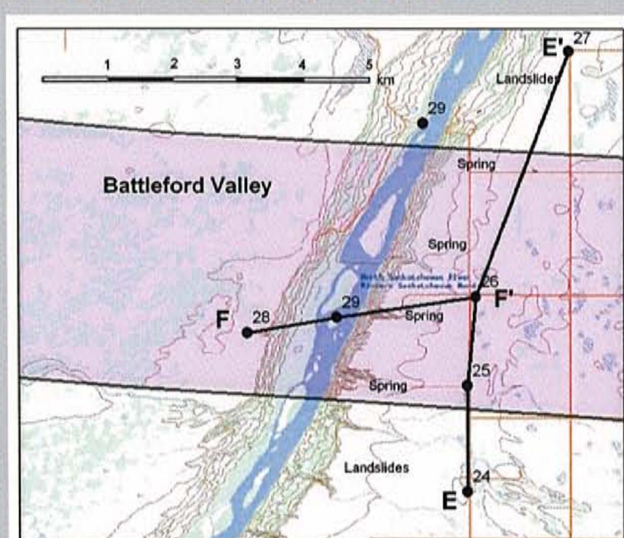
Battleford valley aquifer



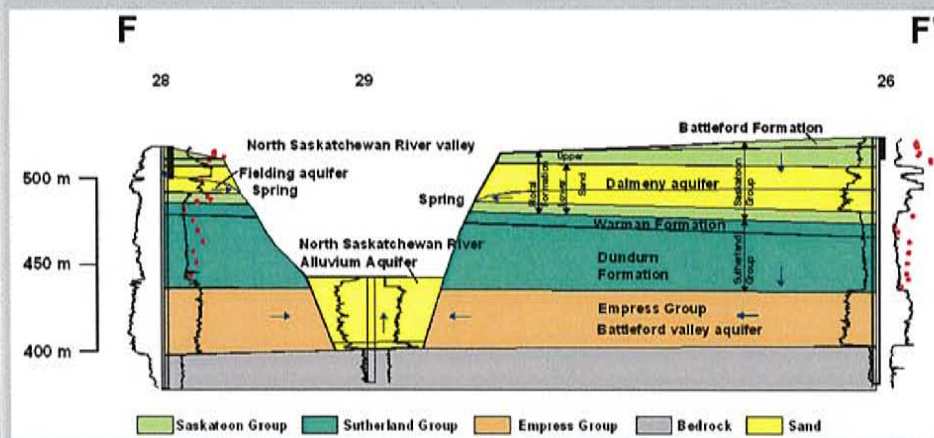
Battleford valley aquifer



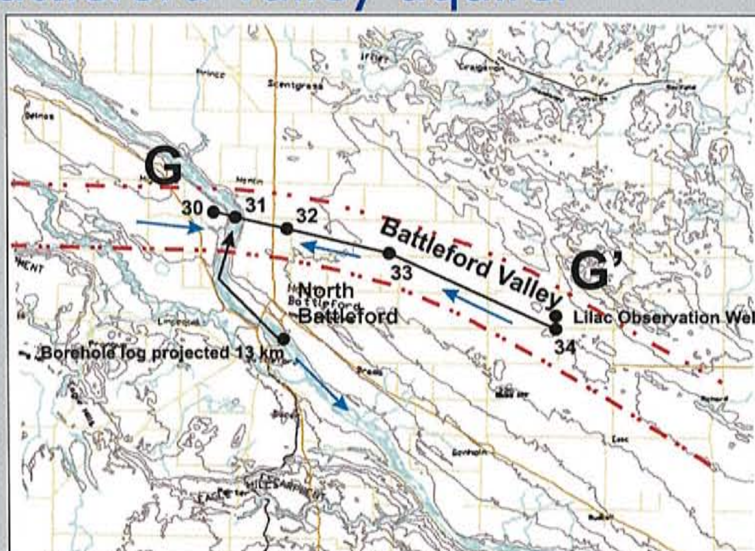
Battleford valley aquifer



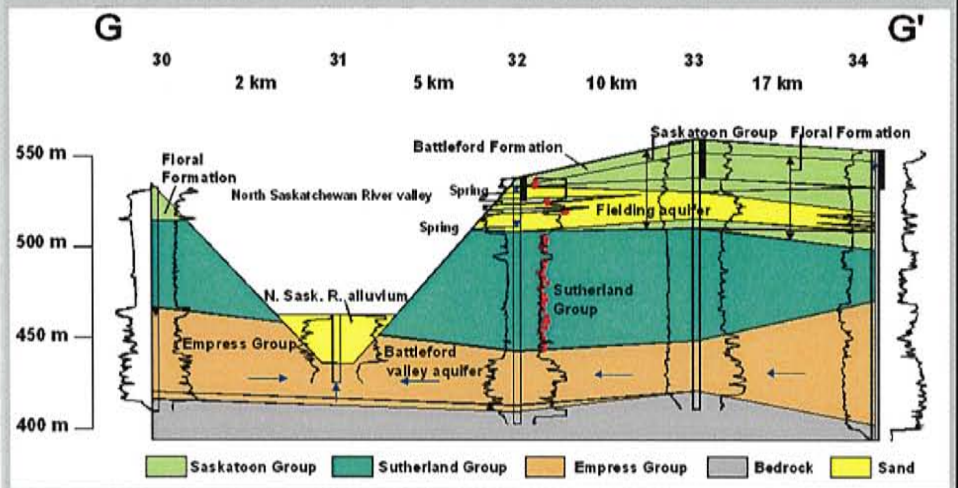
Battleford valley aquifer



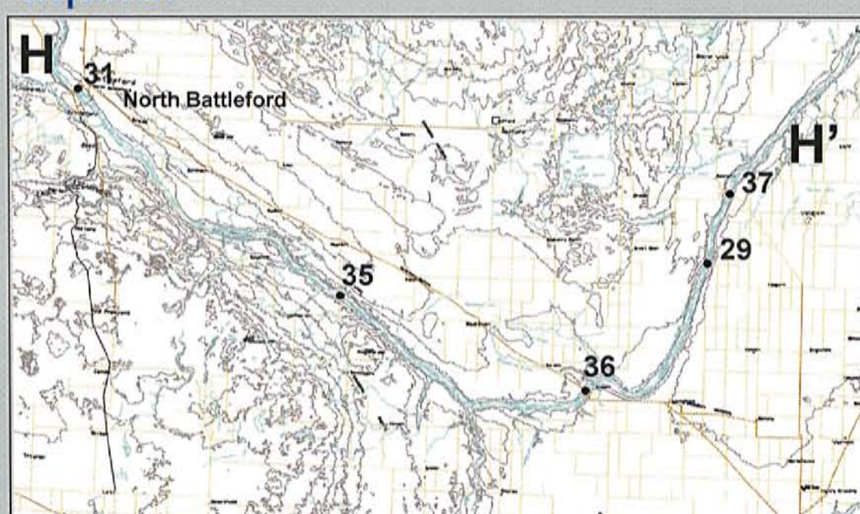
Battleford valley aquifer



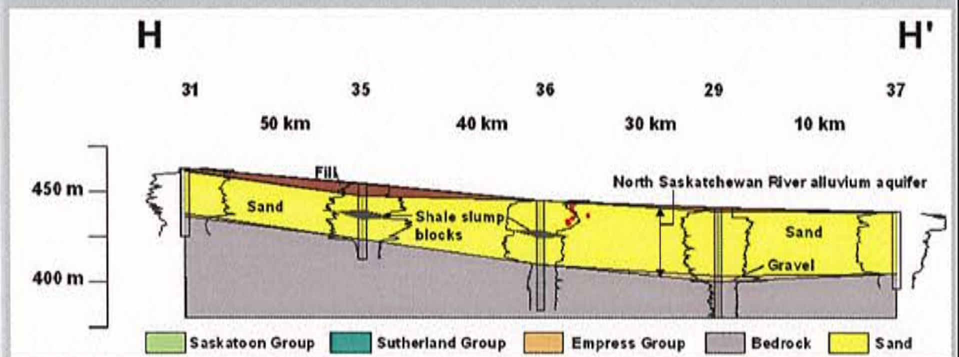
Battleford valley aquifer



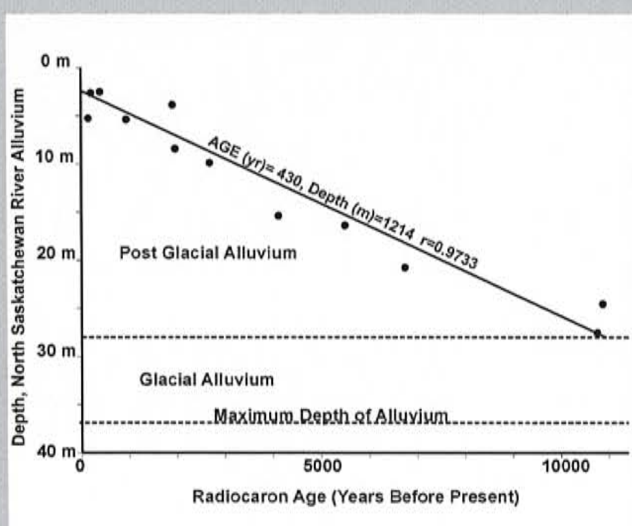
North Saskatchewan River alluvium aquifer



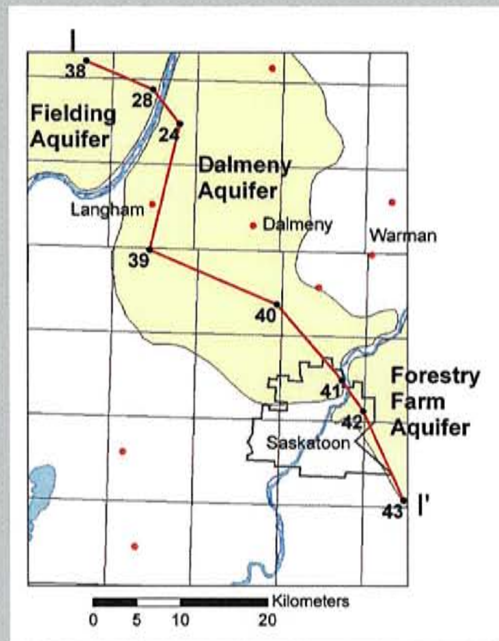
North Saskatchewan River alluvium aquifer



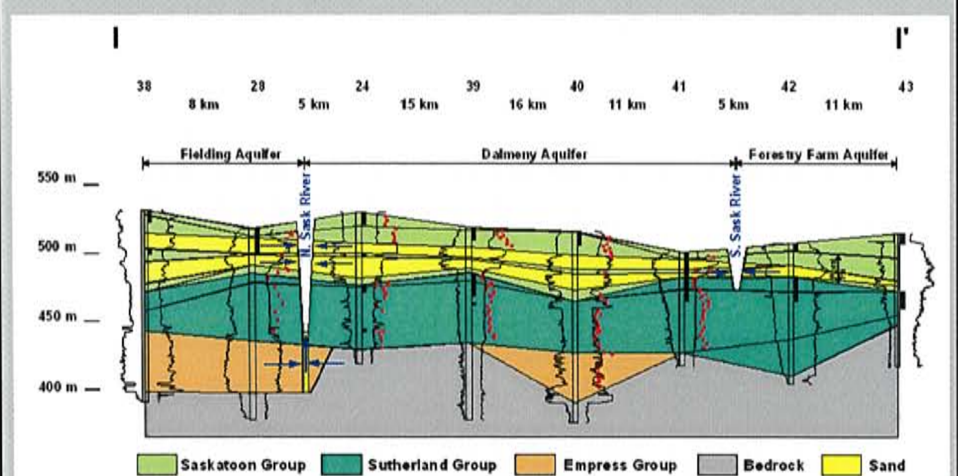
North Saskatchewan River alluvium



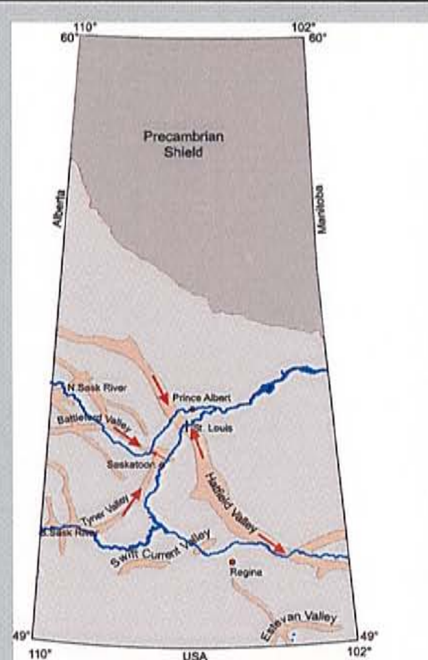
Fielding, Dalmeny, and Forestry Farm aquifers



Fielding, Dalmeny, and Forestry Farm aquifers

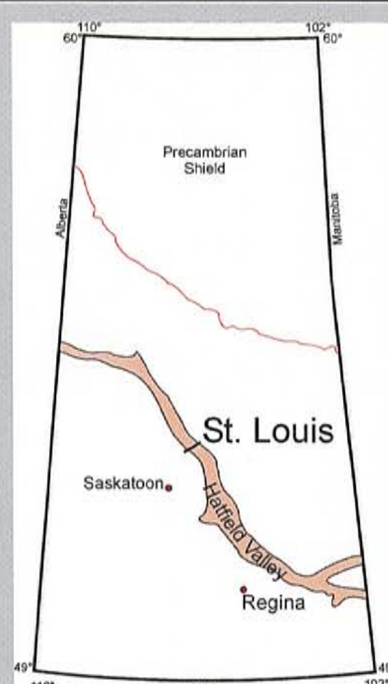


Major bedrock valleys



Major aquifers in Saskatchewan yielding potable water
(Source: H. Maathuis, Saskatchewan Research Council)

Hatfield valley aquifer



The borehole log

- The borehole log is the building block of cross sections.

Borehole Logs should include all geologic and geotechnical information such as :

- Carbonate content
- Grain size
- Preconsolidation pressures
- Natural water content
- Atterberg limits
- Oxidized zones
- Density
- Piezometer depths and heads
- Cored intervals
- Geophysical logs
- Any other measurement that lends itself to a depth curve

Conclusion - the borehole log

- Now you are ready to draw a cross section

The End

Thank you

GLACIAL GEOLOGY OF SOUTHERN SASKATCHEWAN

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ABSTRACT
The glacial geology of southern Saskatchewan will be considered under three sections: namely stratigraphy, geological processes and groundwater occurrence. Sequence stratigraphy is the technique utilized to separate and map stratigraphic units. A sequence is "A relatively conformable succession of genetically related strata bounded by unconformities". Unconformities are defined as surfaces of erosion or nondeposition that represent gaps in geologic time. In Saskatchewan, these unconformities are indicated by oxidized zones and carbonate content of the tills (lithology). These sequences are called formations which are composed of till and associated stratified deposits. Formations are combined into groups and divided into members.

Geological processes considered here include: (1) outwash of stratified sediments derived from melting glaciers, (2) inwash of deltaic stratified sediments deposited from extraglacial streams, and (3) salt collapse structures which occurred during the last glaciation about 20,000 years ago.

In Saskatchewan, significant groundwater resources occur in the preglacial Tyner and Battleford bedrock valleys and associated Tessier, Fielding, Dalmeny, and Forestry Farm aquifers in the Floral Formation. Significant groundwater resources also occur in the Hatfield bedrock valley aquifer which extends across Saskatchewan.

RÉSUMÉ
La géologie glaciaire de la Saskatchewan sera examinée en trois sections: stratigraphie, processus géologiques, et présence de nappes phréatiques. La stratigraphie en séquences est la technique utilisée pour séparer et mapper les unités stratigraphiques. Une séquence est "une succession relativement concordante de strates génétiquement apparentés et bornés par des discordances". On définit les discordances comme des surfaces d'érosion ou de non-dépôt représentant des brèches dans le temps géologique. En Saskatchewan, ces discordances sont signalées par des zones oxydées et par le contenu en carbonate de l'argile à blocaux (lithologie). Ces séquences, appelées formations, sont composées d'argile à blocaux et autres gisements stratifiés. Les formations sont combinées en groupes et divisées en membres.

Les processus géologiques étudiés ici comprennent: (1) l'épandage de sédiments stratifiés provenant de la fonte des glaciers, (2) la rétention de sédiments stratifiés deltaïques déposés par les cours d'eau extraglaciaires, et (3) les structures d'effondrement qui prirent place pendant la dernière glaciation, il y a environ 20 000 ans.

En Saskatchewan, des ressources phréatiques importantes existent dans les vallées préglaciaires à socle rocheux de Tyner et de Battleford, ainsi que dans les aquifères annexes de Tessier, Fielding, Dalmeny et Forestry Farm, dans la Formation Florale. Des ressources phréatiques importantes existent également dans l'aquifère sur roche-mère de la vallée Hatfield, qui s'étend sur toute la Saskatchewan.

1. INTRODUCTION

In considering the subject of geology of glacial deposits in southern Saskatchewan (Fig. 1), the following subjects of (1) stratigraphy; (2) geological processes including outwash and inwash of stratified deposits, and salt collapse; and (3) the occurrence of groundwater will be discussed.

2. STRATIGRAPHY

2.1 Introduction

In dealing with the stratigraphy of glacial deposits, the use of the sequence stratigraphy approach, a technique used commonly in the petroleum industry, will be utilized. A sequence is "A relatively conformable succession of genetically related strata bounded by unconformities" (Mitchum 1977). An unconformity is a surface of erosion or nondeposition that represents a time gap in the geologic record. The stratigraphic unit formation is used here to classify tills and their associated stratified deposits, and like sequences, formations are bounded by unconformities. Formations are defined primarily on the basis of the nature of the tills which have unique lithologies and stratigraphic position. In Saskatchewan, carbonate content is the most distinct criterion in identifying tills. Because of the paucity of thick exposures of glacial deposits, geologic interpretations are based almost entirely on boreholes and geophysical logs (Table 1).

2.2 Bedrock surface

The bedrock surface is normally located between the bedrock and the overlying glacial deposits (drift). In the preglacial Tyner and Battleford valleys, however, the bedrock surface is located between Cretaceous bedrock and overlying preglacial gravels (see Empress Group below).

2.3 Information

The stratigraphic interpretation is based on more than 3000 rotary-drill (Fig. 2) boreholes, all of which have driller's logs and electric logs; some of which have rotary-drill cutting samples (Fig. 3) and side-wall cores (Figs. 4, 5); and about 200 boreholes have the additional gamma-ray and calliper geophysical logs (Fig. 6). Carbonate content was determined on all cuttings and cores. The main contributors to this data bank are Saskatchewan Research Council, Saskatchewan Highways and Transportation, and Saskatchewan Institute of Pedology.

2.4 Compilation of borehole logs

The borehole log (Fig. 6) at the Sutherland overpass along Highway 5 in Saskatoon exhibits gamma-ray, electric, and calliper geophysical logs; carbonate content of selected rotary cutting and drive-core samples; and geologic descriptions of the cutting and core samples. A geologic strip log is shown in the center of the log, and the oxidized zones are shown as black bars to the right of the strip log.

2.5 The role of oxidized zones

Oxidized zones form when gray ferrous iron oxidizes to brown ferric iron. Oxidized zones are the most common indicator of weathering. The top of oxidized zones are unconformities (Figs. 7-10). According to Christiansen (1992), stratified deposits are associated with till as follows. (1) "If an intertill deposit is oxidized and the overlying till is unoxidized (Fig. 7), the intertill deposit is associated with the underlying till. (2) If an intertill deposit is unoxidized, and the underlying till is oxidized (Fig. 8), the intertill deposit is associated with the overlying till. (3) If the lower part of an intertill deposit is oxidized and the upper part is unoxidized (Figs. 9, 10), the lower part is associated with the underlying till and the upper part is associated with the overlying till. (4) If an oxidized zone penetrates more than one till (Fig. 11) or if both tills are unoxidized (Fig. 12, Floral/Dundurn), the tills can be separated only on the basis of lithology which in this case is carbonate content.

2.6 Stratigraphic Units

2.6.1 Empress Group

The Empress Group (Fig. 13) is composed of stratified sediments between bedrock and till (Whitaker and Christiansen, 1972). The sediments consist of a lower preglacial unit of sand and chert and quartzite gravel and an upper proglacial unit composed stratified sediment which include igneous, metamorphic, and carbonate clasts (Fig. 13). The lower unit is restricted to fills in preglacial valleys, whereas the upper unit occurs in both preglacial valleys and upland areas. The basal contact of the Empress Group is an erosional unconformity.

2.6.2 Sutherland Group

The Sutherland Group was divided into Mennon, Dundurn, and Warman formations by Christiansen (1992) on the bases of carbonate content and stratigraphic sequence (Fig. 6, Tables 1, 2). The Dundurn Formation is divided informally into lower and upper units on carbonate content (Fig. 6, Table 2).

2.6.3 Saskatoon Group

The Saskatoon Group is divided into Floral and Battleford formations on preconsolidation pressure of tills, structure, staining, and carbonate content of tills (Fig. 14, Tables 1, 2). Till of the Floral Formation has a preconsolidation pressure of 1800 ± 200 kPa, whereas till of the Battleford Formation has a preconsolidation pressure of 400-750 kPa (Sauer et al., 1993). Till of the Floral Formation is jointed and stained, whereas till of the Battleford Formation is massive and unstained.

Table 1. Carbonate content of tills in southern Saskatchewan.

Stratigraphic Unit	No. of samples	Mean mL CO_2/g	SD mL CO_2/g
Saskatoon Group			
Battleford Formation	552	28.2	13.5
Floral Formation	1855	38.2	13.9
Sutherland Group			
Warman Formation	561	16.6	5.0
Dundurn Formation	1048	29.1	8.3
Mennon Formation	310	14.1	4.5
Saskatoon Group	**2407**	**35.9**	**14.4**
Sutherland Group	**1919**	**23.0**	**9.7**

Table 2. Carbonate content of tills at Sutherland Overpass 04 and SHT Eagle 196.*

Stratigraphic unit	No. of samples	Mean mL CO_2/g	SD mL CO_2/g
Saskatoon Group			
Battleford Formation	2	32.8	8.1
Floral Formation			
Upper till	4	38.3	5.5
Lower till	9	32.9	4.5
Floral Formation (all till samples)	13	34.6	5.3
Sutherland Group			
Warman Formation	16	14.3	3.5
Dundurn Formation			
Upper till	17	27.5	4.3
Lower till	16	20.5	3.8
Dundurn Formation (all till samples)	33	24.1	5.4
Mennon Formation	36	11.4	2.0

Stratigraphic unit	No. of samples	Mean mL CO_2/g	SD mL CO_2/g
Saskatoon Group	**15**	**34.3**	**5.4**
Sutherland Group	**85**	**16.9**	**7.0**

*Borehole log at same location as 04 but is not shown.

2.7 Methods of Separating Stratigraphic Units

2.7.1 Phase No. 1

Divide a column on the right side of the borehole log into bedrock, Empress Group, and till and intertill stratified deposits (Fig. 15). The contact between bedrock and the Empress Group is an erosional unconformity.

2.7.2 Phase No. 2

Divide the tills and intertill stratified deposits into Sutherland and Saskatoon groups (Fig. 16). The contact between the two groups is an unconformity as evidenced by an oxidized zone on top of the Sutherland Group and by the difference in carbonate content between the Sutherland and Saskatoon groups (Fig. 16, Table 2).

2.7.3 Phase No. 3

Divide the Sutherland Group into Mennon, Dundurn, and Warman formations and the Saskatoon Group into the Floral and Battleford formations on carbonate content of tills and the oxidized zone in the upper part of the Warman Formation (Fig. 17). The contacts between the formations are unconformities.

2.7.4 Phase No. 4

Divide the Dundurn and Floral formations into lower and upper units on carbonate content in the Dundurn Formation and on an oxidized zone in the Floral Formation (Fig. 18). Because the difference in carbonate content between the lower and upper units of the Dundurn Formation have not been shown to have regional extent, the formation cannot be formally subdivided and named at this time. Even though the oxidized zone within the Floral Formation indicates that the formation was deposited during two glaciations, composition differences do not permit lithological separation at this time.

2.8 Source of Tills

2.8.1 Glacial ice accumulation

Two centers of glaciation have been postulated by Vincent and Prest (1987), one to the north in the Keewatin area and another to the east in Labrador (Fig. 19). Schreiner (1990) used these centers of ice accumulation to explain the south and west flow of ice in Saskatchewan. Schreiner (1990) concluded that the Keewatin center was the main center of ice accumulation for all tills except till of the Dundurn Formation. He sited the presence of Hudson Bay Omar erratics in the western plains (Prest and Nielsen, 1987) and westward striations in Manitoba as evidence for an eastern ice center in Labrador (Fig. 19). This eastern source of ice and the presence of carbonate rocks in Manitoba would explain the higher carbonate content in the till of the Dundurn Formation (Table 1, 2).

2.8.2 Glacial Stripping

According to Schreiner (1990) progressive glacial stripping of Cretaceous shales occurred in a band extending from as far north as Deep Bay, Reindeer Lake to near Prince Albert (Fig. 20). During this glacial stripping, Cretaceous shales were removed from Precambrian Shield and the Lower Cretaceous sandstones south of the Shield. After loading up with Cretaceous shales, the glacier advanced southward to its terminus as described by Schreiner (1990, p. 91, 92) in the following summary.

2.8.3 Summary

"*In summary, the evidence indicates that successive ice advances came off the resistant shield unsaturated with material. When the ice encountered the sedimentary rocks, it selectively eroded the softer deformable bedrock units. The ice became saturated over a short distance with relatively uniform material which dominated the lithology of the glacial load. The load was then carried in the ice without the incorporation of much new material as the ice extended to its terminus. The load was then let down as the ice ablated.*"

3. GEOLOGICAL PROCESSES

3.1 Introduction

The geological processes that will be considered here include outwash and inwash of stratified deposits and the Saskatoon Low salt collapse structure.

3.2 Outwash

3.2.1 Introduction

Outwash is mainly silt, sand, and gravel "washed out" from a glacier by meltwater. Most outwash in Saskatchewan was deposited where subglacial channels discharge meltwater to form fans such as the Welby sand plain (Christiansen, 1962).

3.2.2 Welby sand plain

The Welby sand plain was formed by sand delivered to a re-entrant in the ice margin by the subglacial Deerhorn channels (Fig. 21). The re-entrant area is defined by the washboard moraine. Figure 22 shows the surficial geology of the same area as shown in Figure 21. The shape of the ice margins is well illustrated by the trend of the washboard moraines, and the direction of glacier movement is shown by the fluting in Figure 22.

The sediments encountered in the Welby borehole include bedrock, Empress Group and Floral and Battleford formations of the Saskatoon Group (Fig. 23). Two aquifers exist in the borehole log, one in the sand of the Empress Group and the other in the Welby sand. Each aquifer has a different water level (Fig. 23) because of the proximity of the Qu'Appelle Valley (Fig. 22). The water levels in the borehole (Fig. 23) were obtained from the abrupt changes in the resistance log in the Empress Group and Welby sand (Fig. 23).

3.3 Inwash

3.3.1 Introduction

Inwash is used here for deltaic sediments brought into ice bound glacial lakes by extraglacial rivers. The Prince Albert delta (Christiansen, 1979) is an example of one of many deltas that formed where the North and South Saskatchewan rivers emptied into glacial Lake Saskatchewan (Fig. 24).

3.3.2 Prince Albert delta

The Prince Albert delta formed where the North and South Saskatchewan rivers and Shellbrook, Sturgeon, and Spruce channels entered Lake Saskatchewan (Fig. 24). The sediment in the Prince Albert delta coarsens upward (Fig. 25) as a result of progradation of the delta. Inwash is finer grained than outwash because inwash is derived from erosion of bedrock and the reworking of glacial deposits, whereas outwash is mainly glacially derived.

3.4 Differentiation of outwash and inwash in borehole logs

Two upward coarsening sequences of silts and sands occur in the Demaine borehole log (Fig. 26). The lower sequence was deposited as outwash during the advance of the glacier that deposited till of the upper Dundurn Formation or as inwash in a proglacial delta that formed during the advance of the upper Dundurn glacier. The upper sequence was deposited as inwash in a proglacial delta during the retreat of the Floral glacier. If this upper sand and silt had been deposited during the retreat of the Floral glacier, it would have become finer grained upward.

3.5 Saskatoon Low salt collapse structure

3.5.1 Introduction

The Saskatoon Low extends southward from Saskatoon (Figs. 27, 28). The thickness of salt in the vicinity of the Saskatoon Low is at least 180 m (Holter, 1969) and the structural closure is at least 150 m suggesting that about 30 m of Prairie Evaporite Formation remains beneath the structure.

3.5.2 Structure

A schematic gravity fault model was utilized to interpret the stratigraphy (Fig. 29). The Saskatoon Low was filled with up to 110 m of till of the Battleford Formation (Fig. 30) and up to 77 m of clay, silt, and sand of the Haultain Member of the Battleford Formation (Fig. 31).

3.5.3 Effective stress-depth profile of till of the Battleford Formation

Prior to the work of Sauer and Christiansen (1991) and Sauer in Christiansen and Sauer (2001), the Battleford Formation was differentiated on the basis of field observations. Till of the Battleford Formation is soft, massive, and unstained, whereas the underlying till of the Floral Formation is hard, jointed, and stained where oxidized (Christiansen, 1992).

In 1966, a borehole was drilled, electric logged, and side-wall cored (Fig. 32). The side-wall cores in the Battleford Formation could be deformed by squeezing them between the thumb and forefinger. Upon hearing about the softened state of the Battleford Formation, Sauer (*in* Christiansen and Sauer, 2001) decided to obtain rotary-drill cores from the same site of the borehole in Fig. 32 and to conduct effective stress measurements on till and the Haultain Member of the Battleford Formation.

The divergence of the preconsolidation pressure from the present overburden curve in the upper 40 m of the borehole log (Fig. 33) was interpreted by Sauer (in Christiansen and Sauer, 2001) as being the result of desiccation of the Haultain Member and the upper part of the till of the Battleford Formation following the drainage of glacial Lake Saskatchewan. The remainder of the preconsolidation curve closely follows the present overburden pressure curve. This similarity of the preconsolidation and present overburden curves (Fig. 33) explains the softness of cores observed in the field.

3.5.4 Origin

Two events are required to explain the stratigraphy in Fig. 29: (1) the Saskatoon Low collapsed from the weight of the Battleford glacier and (2) the collapse of the Saskatoon Low provided the environment for compressive flow (Sauer *in* Christiansen and Sauer (2001)). During compressive flow of the glacier, the previously faulted Bearpaw (Fig. 29, 3a, b, c), Dundurn (6), and Floral (7) formations were sheared from the Saskatoon Low. The base of the glacially eroded Saskatoon Low is the Ardkenneth Member of the Bearpaw Formation (Fig. 29, 3b). The Ardkenneth Member resisted shearing by the Battleford glacier because of its sandier composition resulting in a higher shear resistance.

4. GROUNDWATER OCCURRENCE

4.1 Tyner valley and Tessier aquifer system

4.1.1 Tyner valley aquifer

The Tyner valley aquifer extended intermittently from the Alberta-Saskatchewan border to its confluence with the Battleford valley north of Saskatoon (Fig. 34).

The Tyner valley aquifer is in preglacial chert and quartzite gravel and overlying glacial sand of the Empress Group (Fig. 35).

The observation well was installed in the Tyner valley near borehole log 9 (Fig. 36). The high head and concentration of constituents in this observation well may be explained by the removal of the Tyner valley aquifer in the vicinity of borehole log 10 (Fig. 36) which impeded groundwater flow northwestward in this part of the Tyner valley.

4.1.2 Tessier aquifer

The Tessier aquifer (Figs. 37-39, 40) is composed of two sands separated by clay in borehole log 12 and till in borehole logs 20-22 (Fig. 39). The clay in borehole log 12 (Fig. 39) and the lower Floral sand in borehole log 21 are oxidized indicating that the lower and upper units of the Floral Formation are separated by an unconformity. The unconformity indicates that the two units in the Floral Formation were deposited by two separate and distinct glaciations.

The Tessier observation well (Figs. 34, 37-39, 40) was completed in sand of the lower Floral Formation (Fig. 39, borehole log 12).

4.1.3 Groundwater flow

Meneley (*in* Christiansen et al. 1970) showed that precipitation recharges the Tessier aquifer and that a portion of the recharge returns to depressions in the land surface (Fig. 38a). Another portion of groundwater recharge flows directly from the land surface into the Judith River Formation and from there to the Tyner valley aquifer. Finally, a portion of the groundwater in the Tessier aquifer flows into the Judith River Formation and from there into the Tyner valley aquifer.

From the Tyner Valley cross section (Fig. 38a, 38b), the groundwater flows northward through the Tyner Valley aquifer (Fig. 34), by the Warman observation well site (Fig. 41), to its confluence with the Battleford valley aquifer, and from there through the Battleford valley aquifer into the North Saskatchewan River (Meneley, 1970).

4.2 Battleford valley and associated aquifers

4.2.1 Battleford valley aquifer

The Battleford valley extends from the Alberta-Saskatchewan border to its confluence with the Tyner valley north of Saskatoon (Fig. 42).

The Battleford valley aquifer is in preglacial chert and quartzite gravel and sand, interbedded (lower unit) and glacial sand and silt (upper unit) of the Empress Group (Fig. 43).

The Lilac observation well was completed in glacial sand and silt of the Empress Group (Fig. 44).

A map showing the location of (a) cross section E-E' across the Battleford valley aquifer, (b) boundaries of the Battleford valley, and (c) the geomorphology of the walls of the North Saskatchewan River valley (Fig. 45).

At borehole sites 24 and 27 (Figs. 45, 46), the North Saskatchewan River eroded into bedrock shales, whereas at borehole sites 25 and 26 (Figs. 45, 46), the valley is eroded into sands of the Empress Group. The angle of repose of the valley wall developed in bedrock (Fig. 45) is about 5°, similar to that in the Denholm landslide (Sauer 1983), whereas the angle of reposed of the valley wall developed in drift over the Battleford valley is about 13°.

The low angle of reposed (5°) for the valley walls at borehole sites 24 and 27 (Figs. 45, 46) and the horst and graben structure of the valley wall at borehole site 27 (Fig. 45) indicate these features are landslides. The amphitheatre features in the east wall of the North Saskatchewan River valley (Fig. 45) are being formed by springhead sapping or piping as a result of groundwater discharging from the Dalmeny aquifer (Fig. 47). The Battleford valley aquifer discharges groundwater into the North Saskatchewan River alluvium (Figs. 47, 48).

4.2.2 North Saskatchewan River alluvium aquifer

At the Hepburn Ferry site (Fig. 49, borehole log 29), the North Saskatchewan River valley alluvium is composed of 3m of basal gravel overlain by 36 m of fine to medium grained sand. In borehole logs 35 and 36 (Fig. 49), 4 and 3 m of bedrock silt and sand were encountered in the alluvium. The toe of the Denholm landslide over-riding the North Saskatchewan River alluvium (Sauer and Christiansen, 1987) provides a model for the bedrock slumping encountered in borehole logs 35 and 36 (Fig. 49).

Radiocarbon dates on wood in the North Saskatchewan River alluvium suggest that deposition of the alluvium began about 11,000 years ago (Fig. 50) and is continuing at a rate of 2.4 mm per year.

4.2.3 Fielding, Dalmeny, and Forestry Farm aquifers

The Fielding, Dalmeny, and Forestry Farm aquifers (Fig. 51) like the Tessier aquifer (Fig. 39) are in lower and upper sands of the Floral Formation separated by oxidized till which indicates that these sands were deposited by two separate glaciations. The Fielding, Dalmeny, and Forestry Farm aquifers are separated by the North and South Saskatchewan river valleys (Fig. 51). The Fielding aquifer discharges groundwater through contact springs into the North Saskatchewan River valley (Figs. 47, 48).

The Dalmeny aquifer discharges groundwater into the North and South Saskatchewan river valleys through the springs (Figs. 47, 51). The Dalmeny observation well was completed in the upper sand of the Floral Formation (Fig. 52).

The Forestry Farm aquifer is in the lower sand of the Floral Formation (Fig. 51). Groundwater discharge has formed the Petursson's Ravine by spring sapping or piping of sand and gravel from the lower sand of the Floral Formation (Fig. 53).

4.3 Hatfield valley aquifer

The Hatfield valley aquifer extends from the Alberta-Saskatchewan to the Saskatchewan-Manitoba borders, a distance of about 800 km (Fig. 54). The valley appears to exhibit a slight gradient to the northwest.

The Hatfield valley aquifer at the St. Louis bridge site is a flowing artesian aquifer from sand and gravel of the Empress Group. A detailed geological and geotechnical cross section display of the St. Louis bridge site will be shown in the poster session.

5. SITE INVESTIGATION FROM A GEOLOGIST'S POINT OF VIEW

5.1 Introduction

The following items should be considered in any geotechnical investigation to provide a geological framework.

5.2 Base of exploration

If the base of exploration is unknown, a rotary-drill borehole should be drilled, sampled at 1.5 to 3 m intervals, and geophysically logged as described by Christiansen (1983). Selected till samples should be submitted for total carbonate content analysis. If the base of exploration is thought to be less than 15 m, auger-flight equipment may be used.

5.3 Piezometers

A single piezometer at a site may define the water table. A nest of two, preferably three piezometers are required to determine the hydraulic gradient and whether the groundwater movement is upward or downward. Saline soils are indicative of upward flow of groundwater (Henry, 2003). The Credit Union Centre and The Saskatoon Field House at the University of Saskatchewan are in areas of upward groundwater flow which have required drainage systems.

5.4 Atterberg limits

Natural water content (Wn) is commonly reported without Atterberg limits (Wp, Wl) and Atterberg limits without natural water content. If the Atterberg limits and natural water content are presented together (Fig. 14), it is possible to separate tills of the Floral and Battleford formations. In till of the Floral Formation (Fig. 14), the natural water content is about equal to the plastic limit, whereas in till of the Battleford Formation, the natural water content is greater than the plastic limit.

5.5 Preconsolidation of tills

It is also possible to separate tills of the Floral and Battleford formations on the effect stress-depth curve (Fig. 14). Till of the Floral Formation has a preconsolidation pressure of about 2000 kPa, whereas till of the Battleford Formation has a preconsolidation pressure of up to only about 500 kPa. Furthermore, it is possible to separate basal meltout tills from ablation meltout tills on the effective stress-depth curve (Fig. 14). Basal meltout till of the Battleford Formation has a preconsolidation of about 500 kPa (Fig. 14), whereas ablation meltout till of the Battleford Formation is normally consolidated.

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The manuscript was read by Mr. M. Simpson, Saskatchewan Research Council and Dr. J.S. Sharma, Professor of Civil Engineering, University of Saskatchewan.

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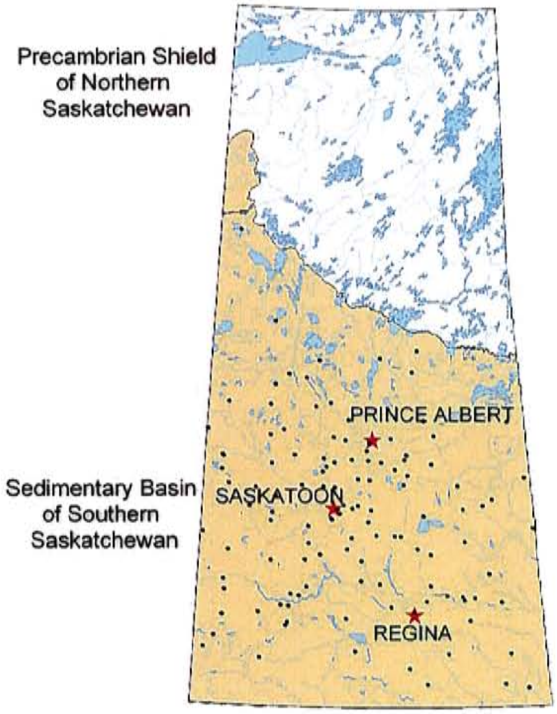


Fig. 1. Map of southern Saskatchewan showing the location of 130 borehole logs selected for carbonate analyses.

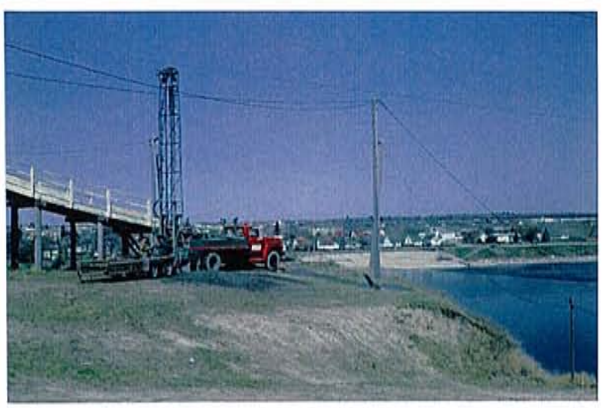


Fig. 2. Rotary-drill equipment drilling a borehole on the University of Saskatchewan campus.

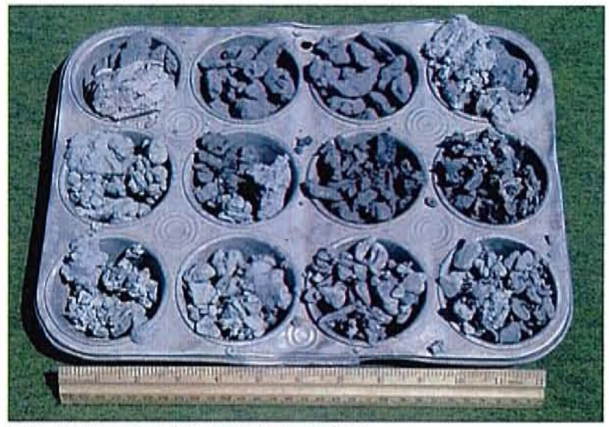


Fig. 3. Rotary-drill cuttings samples.

Fig. 4. Side-wall coring equipment (Morrison, 1969).

Fig. 5. Side-wall cores.

SHT 73-B/2 2003
Borehole 04 Sutherland Overpass
SE-16-25-36-5-W3

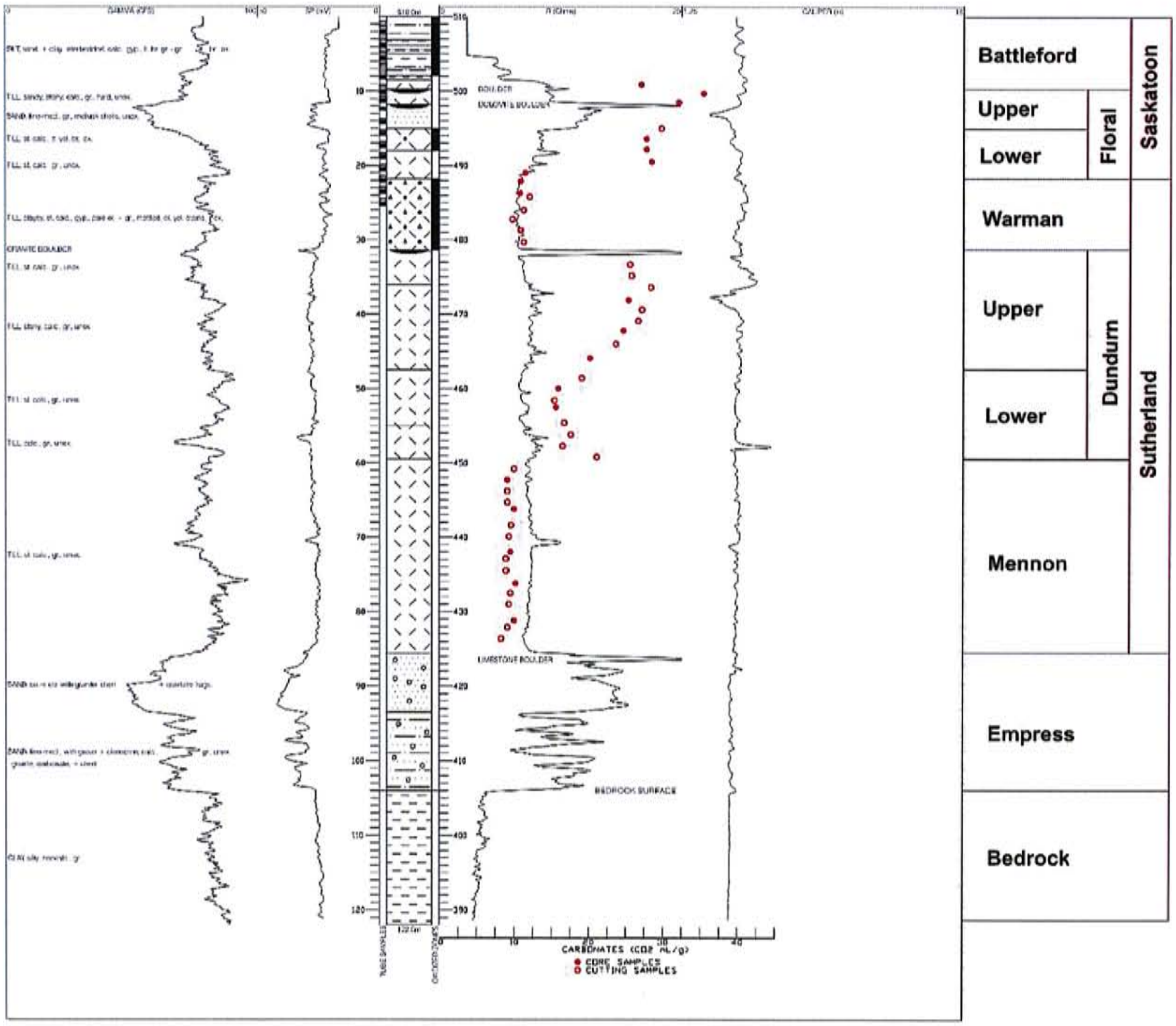


Fig. 6. Saskatchewan Highways and Transportation borehole log 04 from the Sutherland Overpass along Highway 5 in Saskatoon showing electric, gamma-ray, and calliper geophysical logs; carbonate content, and geologic strip logs and sample descriptions.

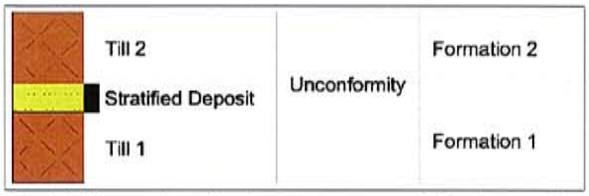


Fig. 7. Unconformity between an oxidized stratified deposit and an overlying unoxidized till.

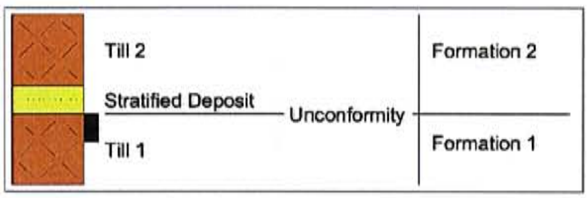


Fig. 8. Unconformity between oxidized till and an overlying unoxidized stratified deposit.

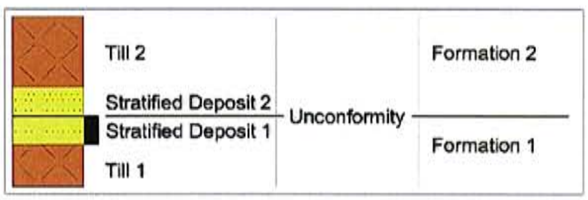


Fig. 9. Unconformity between an oxidized stratified deposit and an overlying unoxidized stratified deposit.

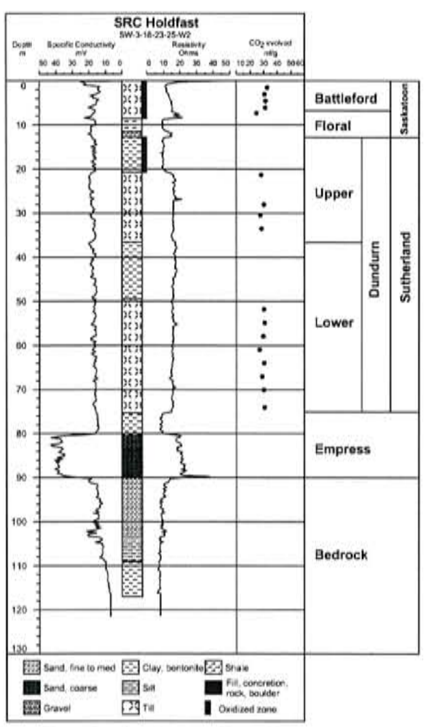


Fig. 10. Borehole log showing an unconformity within the stratified deposits between tills of the Dundurn and Floral formations.

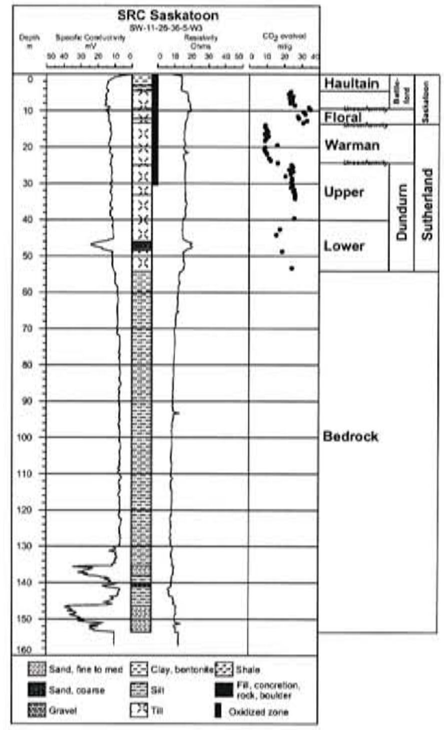


Fig. 11. Borehole log showing three unconformities in one oxidized zone based on the carbonate content of tills.

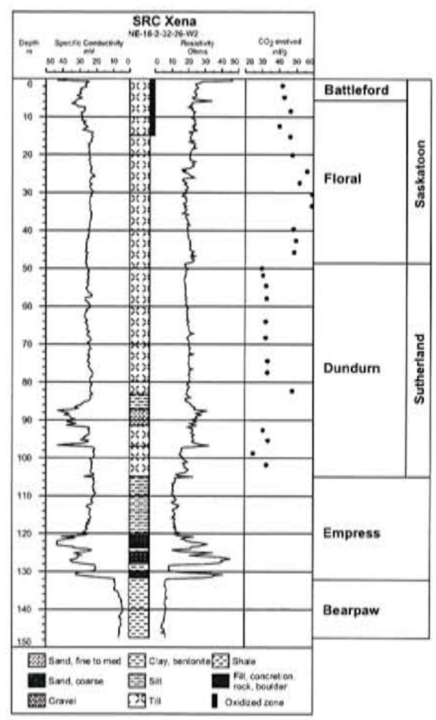


Fig. 12. Borehole log showing an unconformity between two unoxidized tills of the Dundurn and Floral formations based on the carbonate content of tills.

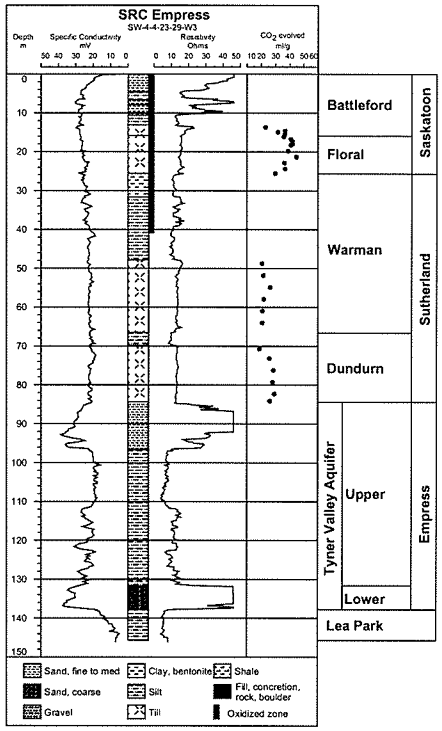


Fig. 13. Borehole log from the type locality of the Empress Group in the Tyner valley at the confluence of the South Saskatchewan and Red Deer rivers.

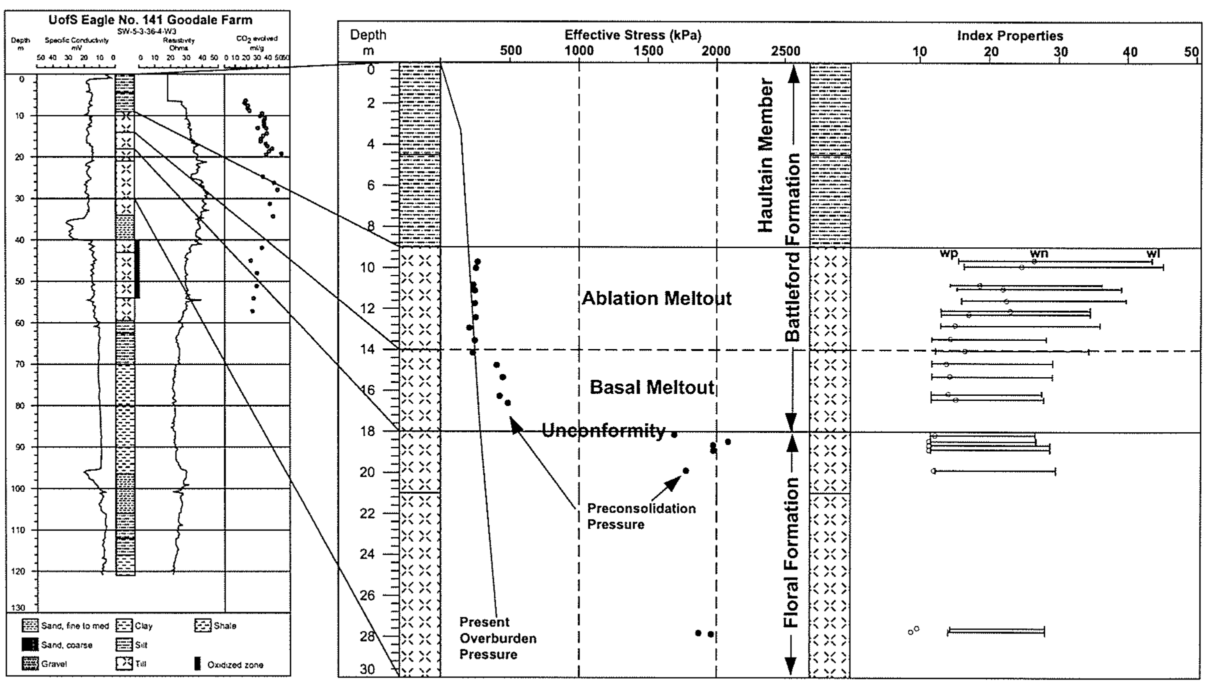


Fig. 14. Preconsolidation pressures and index properties of tills of the Floral and Battleford formations at the Goodale Farm site (Eagle 141). From Sauer et al. 1993.

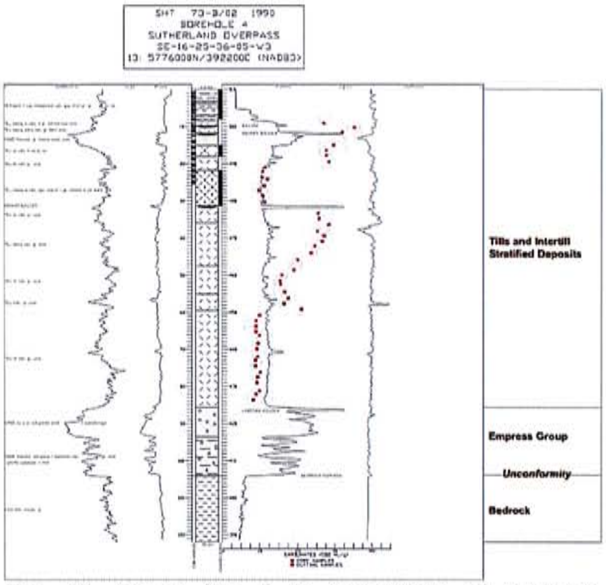


Fig. 15. Phase No. 1 in separation of bedrock, Empress Group, and tills and intertill stratified deposits.

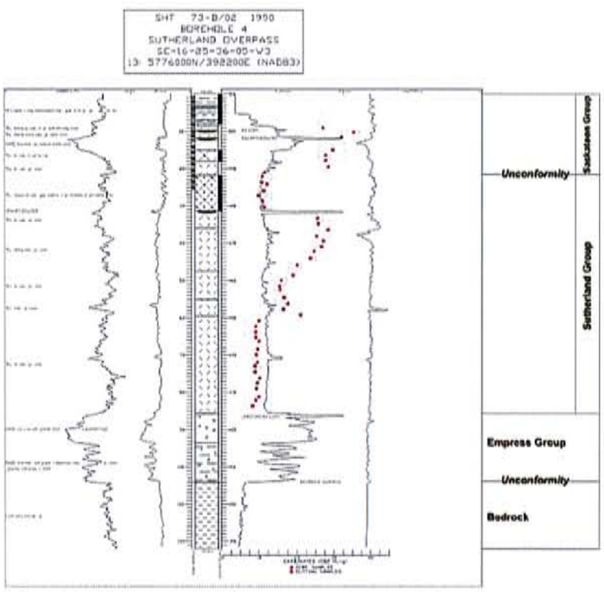


Fig. 16. Phase No. 2 in separation of Sutherland and Saskatoon groups.

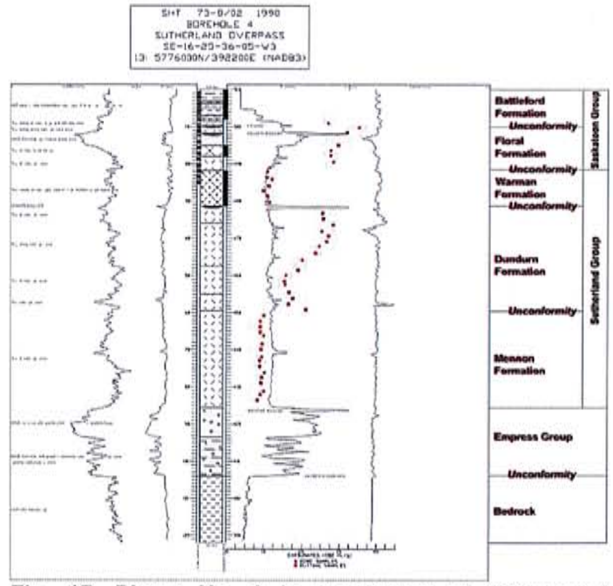


Fig. 17. Phase No. 3 in separation of Sutherland Group into Mennon, Dundurn, and Warman formations and the Saskatoon Group into Floral and Battleford formations.

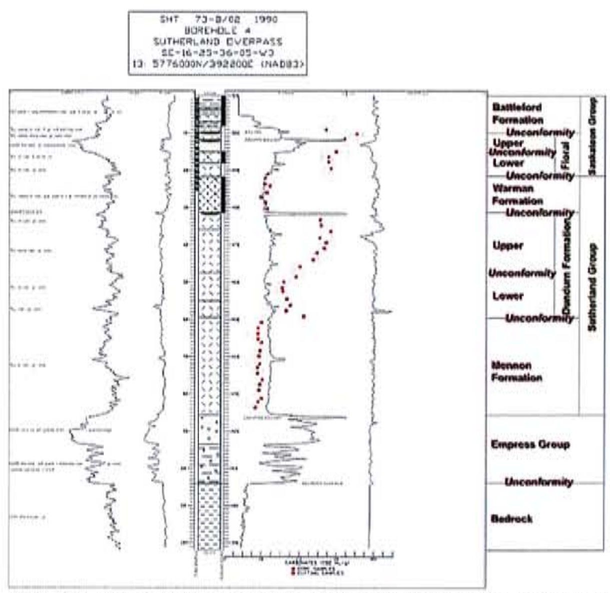


Fig. 18. Phase No. 4 of an informal separation of lower and upper units in the Dundurn and Floral formations.

Fig. 19. Map showing the location of the Keewatin and Labrador ice centers from Vincent and Prest (1987, Fig. 4). The arrows suggest the general flow of ice from these two centers.

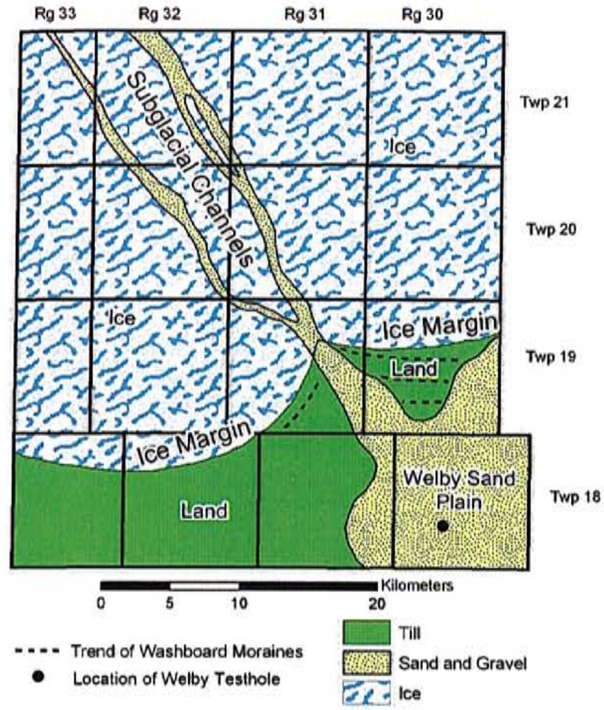


Fig. 21. Phase 1 of the origin of the Welby sand plain.

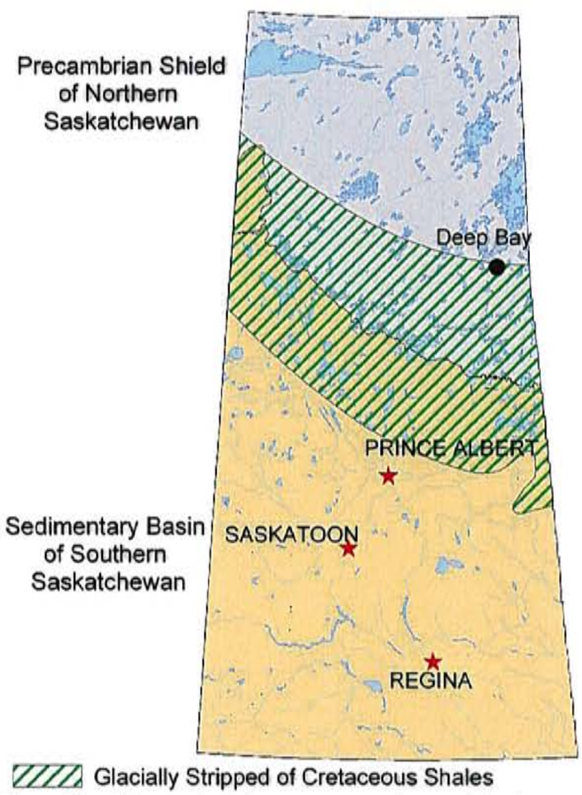


Fig. 20. Map showing progressive stripping of Cretaceous shales during Mennon, Dundurn, Warman, Floral and Battleford glaciations undifferentiated.

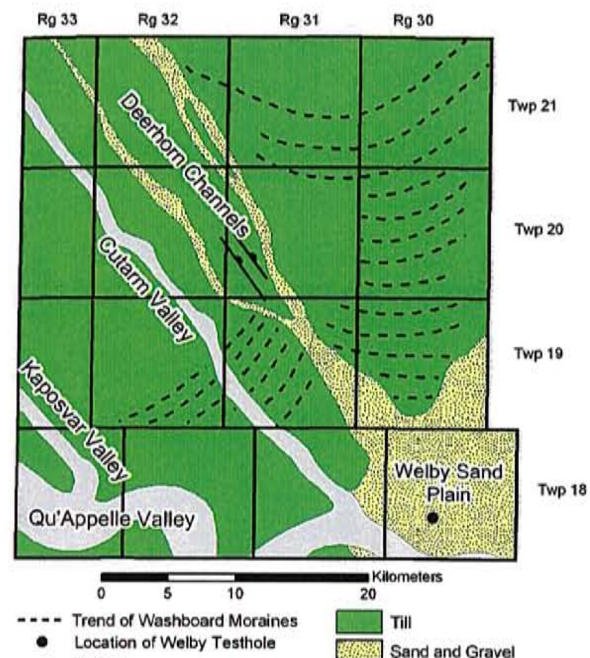


Fig. 22. Phase 2 of the origin of the Welby sand plain.

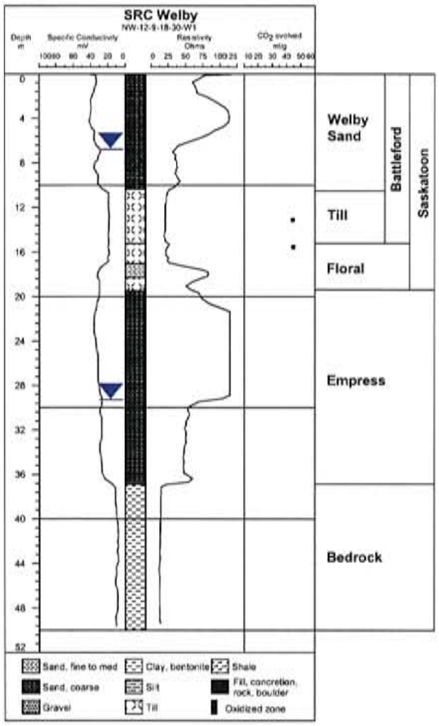


Fig. 23. Welby borehole log showing stratigraphy and groundwater levels.

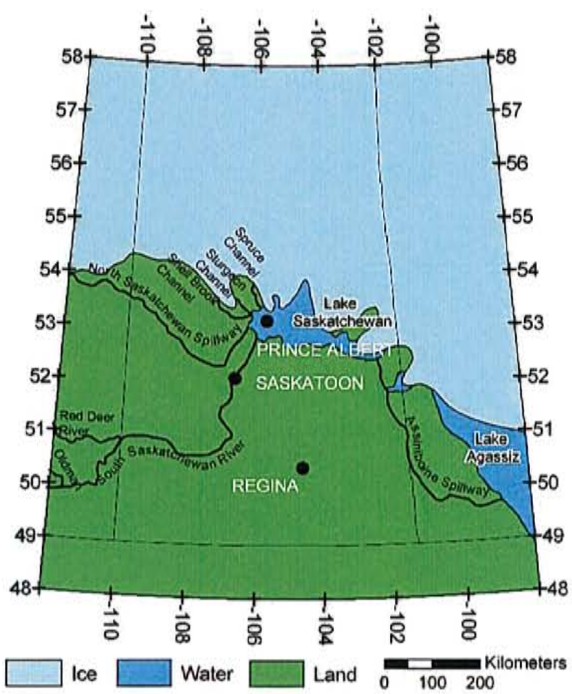


Fig. 24. Prince Albert delta forming in glacial Lake Saskatchewan 11500 years ago (Christiansen, 1979).

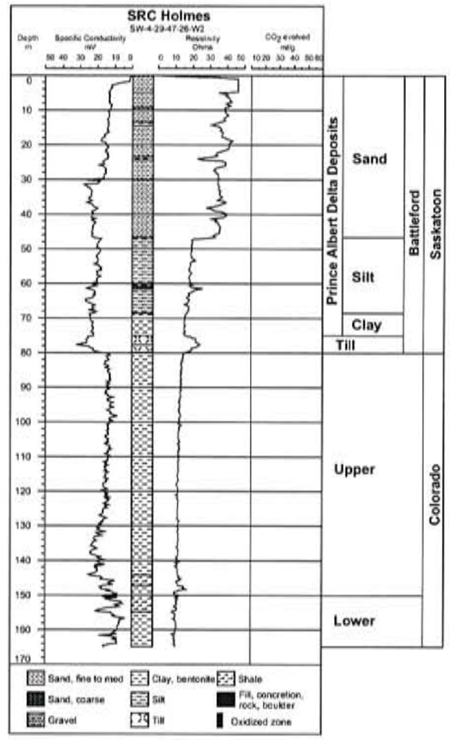


Fig. 25. Borehole log showing coarsening upward in the Prince Albert delta deposits.

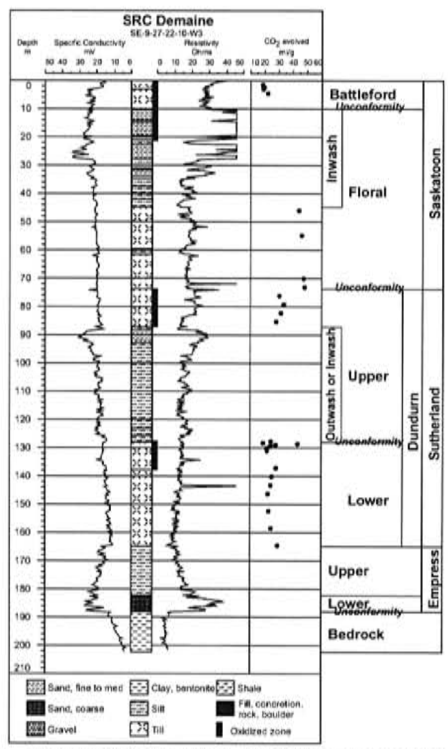


Fig. 26. The differentiation of outwash and inwash in the Demaine borehole log.

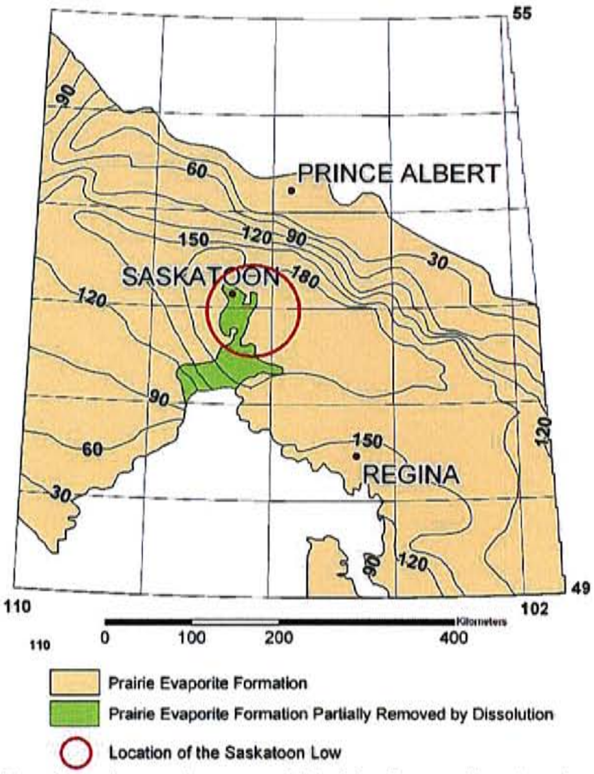


Fig. 27. Isopach map of Prairie Evaporite showing location of Saskatoon Low. Modified slightly from Holter (1969).

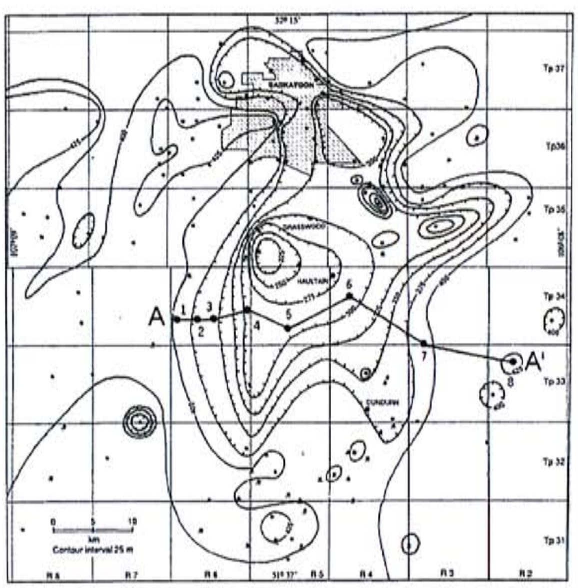


Fig. 28. Structure contour map on top of the Lea Park Formation (Christiansen and Sauer, 2001) showing the location of cross section A-A'.

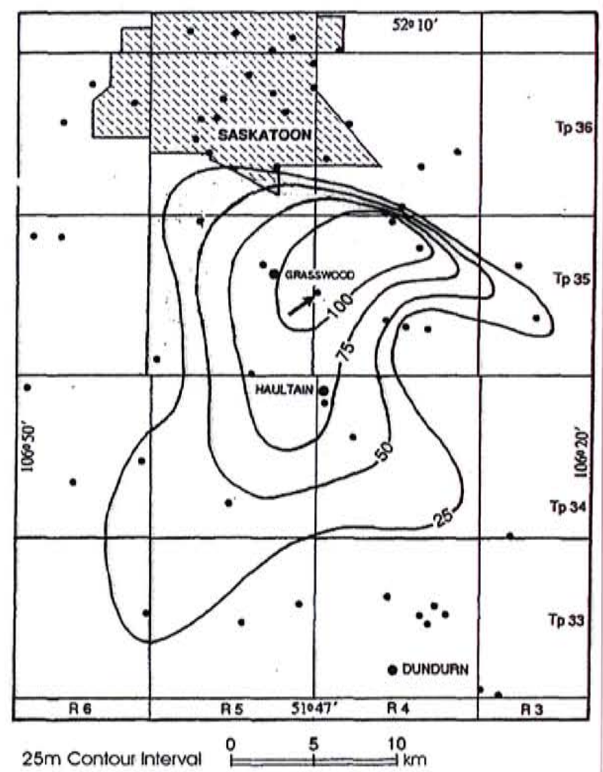


Fig. 30. Isopach map of till of the Battleford Formation. Arrow points to location of Figs. 32, 33.

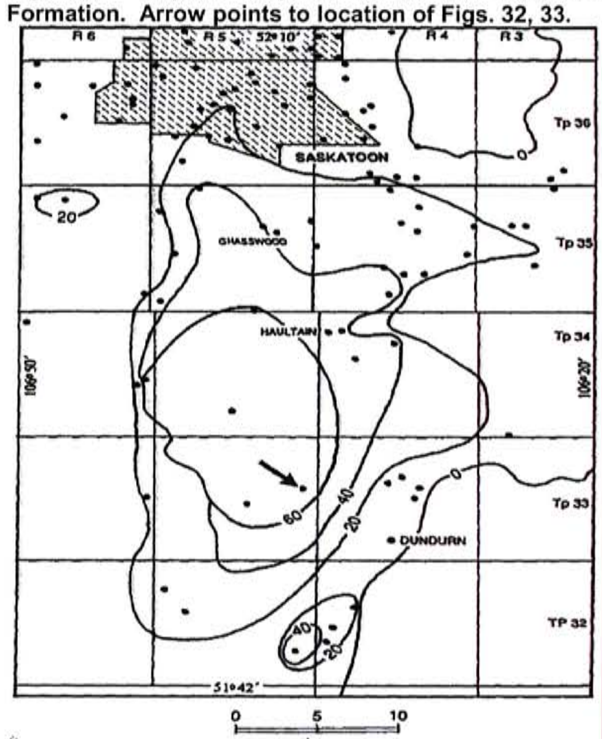


Fig. 31. Isopach map of the Haultain Member of the Battleford Formation. Arrow points to location where the Haultain Member is up to a maximum of 77 m thick.

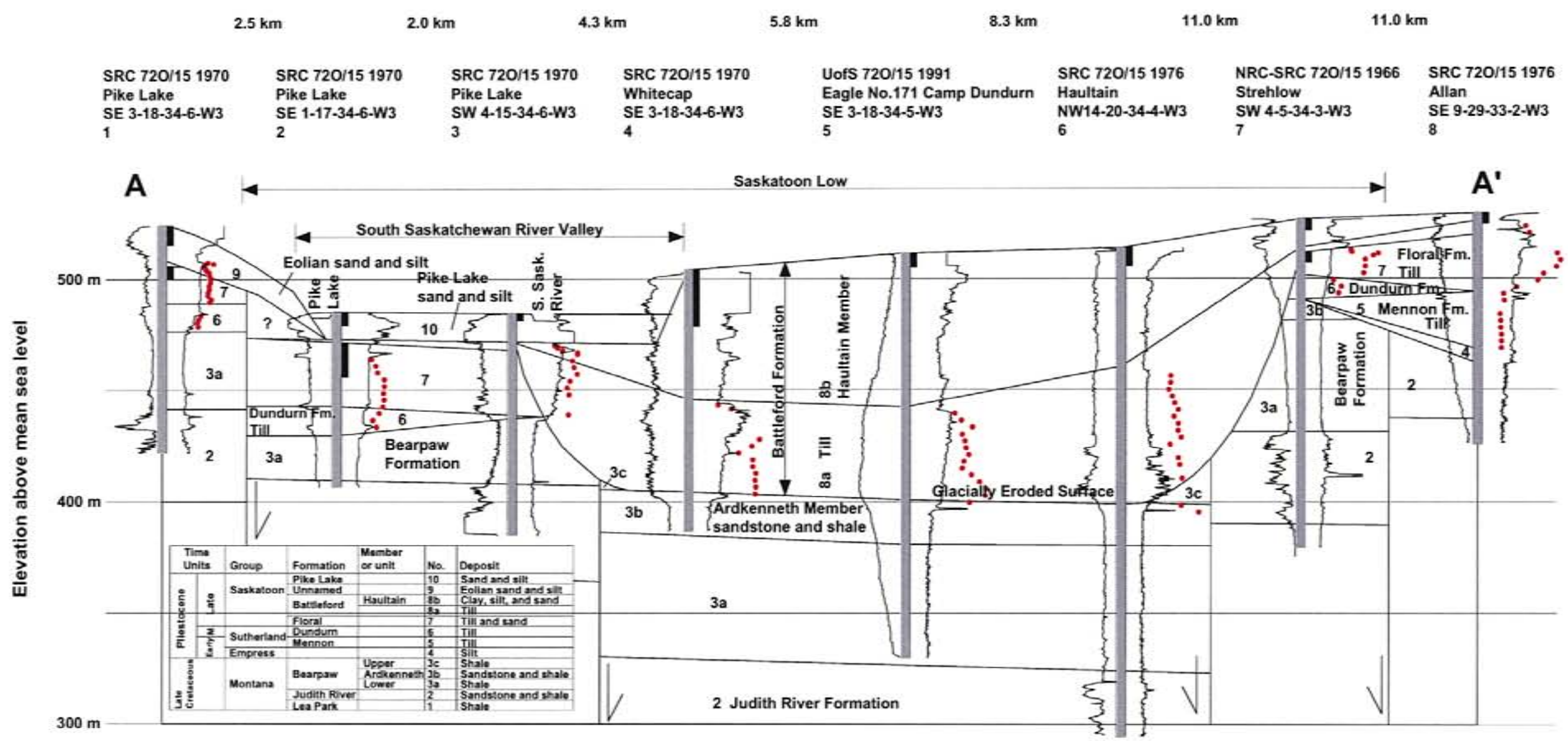


Fig. 29. Cross section A-A' across the Saskatoon Low.

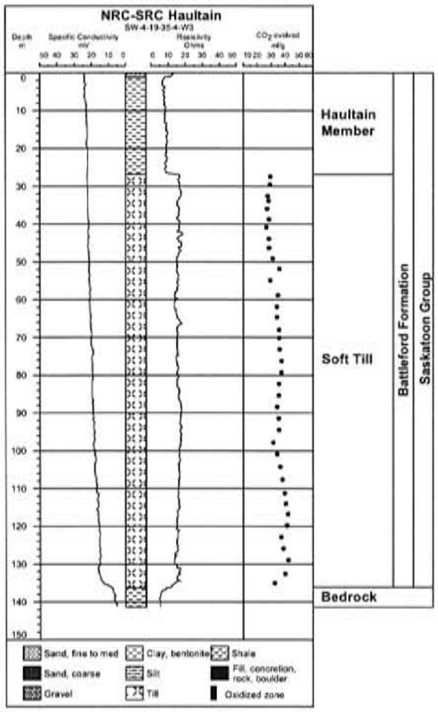


Fig. 32. NRC-SRC Haultain SW-04-19-35-04-W3 borehole log obtained in 1966.

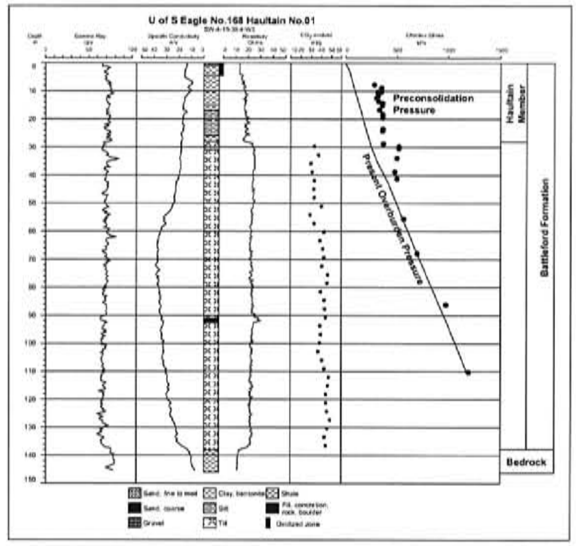


Fig. 33. U of S Eagle No. 168 (SW-04-19-35-04-W3) borehole log (a) and effective-depth profile (b) for till and Haultain Member of the Battleford Formation.

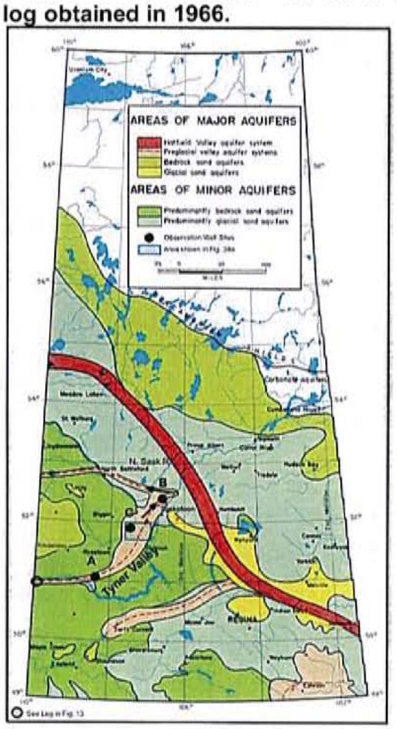
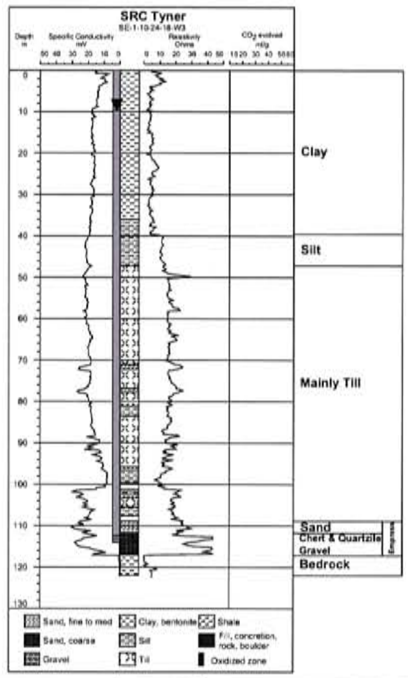


Fig. 34. Brochure of southern Saskatchewan (Christiansen et al., 1970) showing major and minor aquifers, location of Fig. 13; and Tyner (A), Warman (B), and Tessier (C) observation wells. Arrows show direction of groundwater flow through Tyner and Battleford valley aquifers.



Constituent	ppm		
Carbonate as CO_3	Nil	**Concentration**	**2819**
Bicarbonate as HCO_3	712	Conductivity (uS/cm)	3090
Sulphate as SO_4	**1150**	**Hardness as $CaCO_3$**	**615**
Chloride as Cl	141	Alkalinity as $CaCO_3$	584
Calcium as Ca	128		
Magnesium as Mg	72	Date of analyses:	
Sodium as Na	600	August 26, 1971	

Fig. 35. Tyner observation well (Fig. 34(A)) is completed in preglacial chert and quartzite gravel and sand of the Empress Group. A chemical analysis is included with concentration, hardness, and sulphate constituents high-lighted.

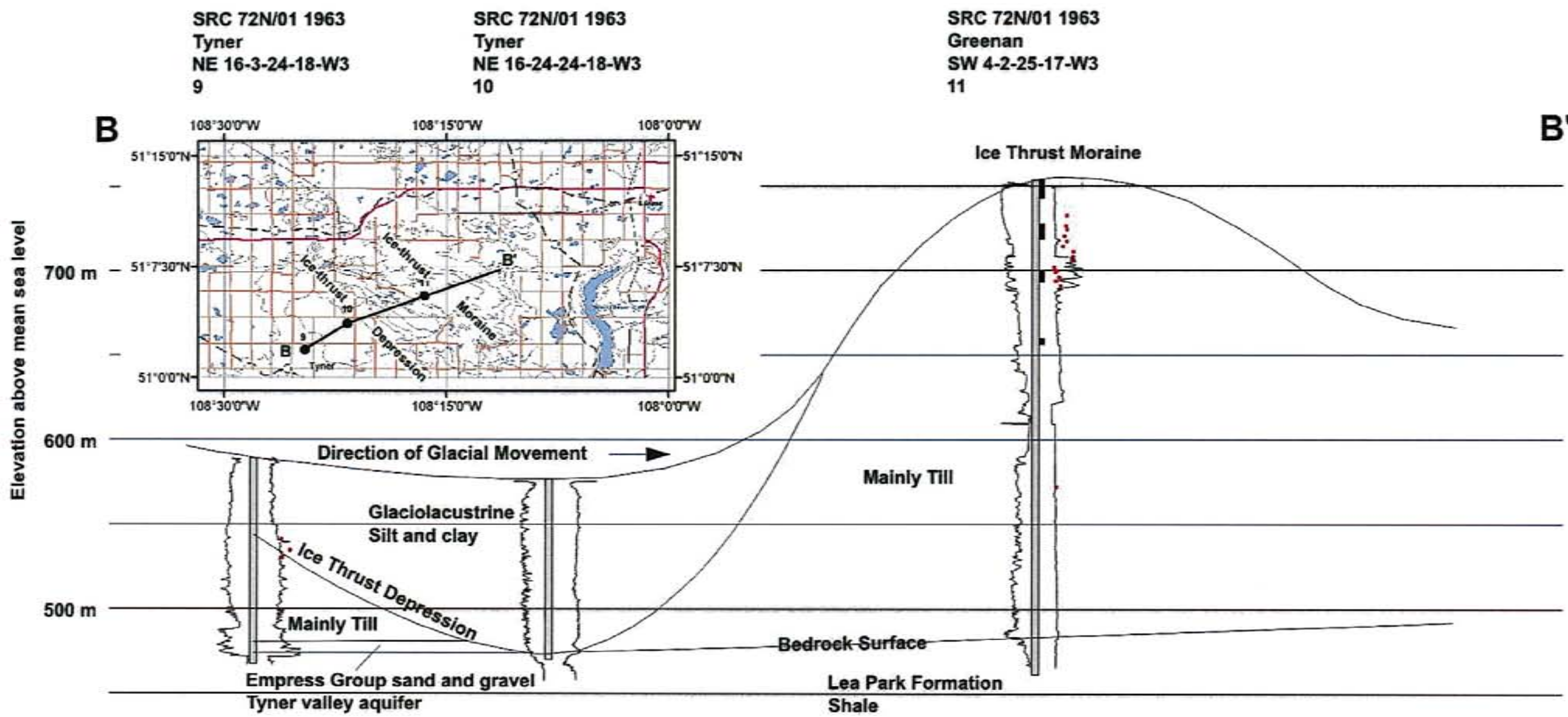


Fig. 36. Cross section B-B' showing that the continuity of the Tyner Valley aquifer was interrupted by glacial erosion of the Empress Group in which the Tyner observation well was completed. From Christiansen and Whitaker, 1976.

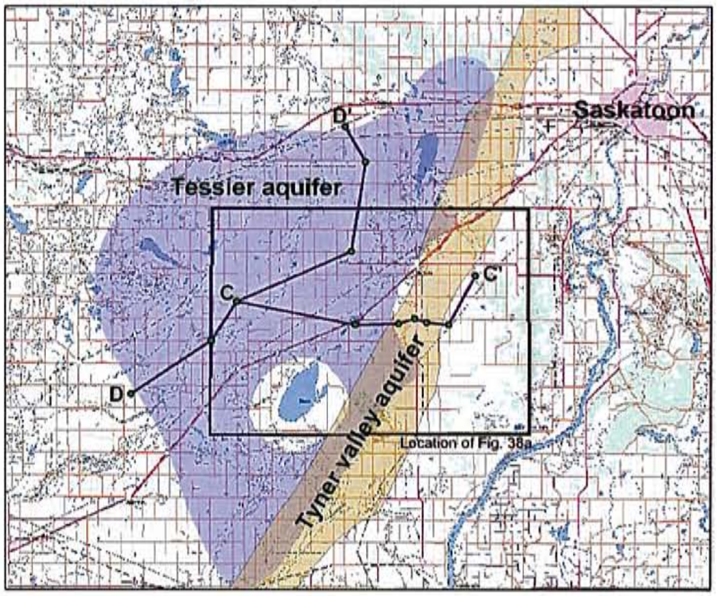


Fig. 37. Tessier and Tyner valley aquifers showing the location of cross sections C-C' and D-D' and the Tessier observation well at "C" of C-C'.

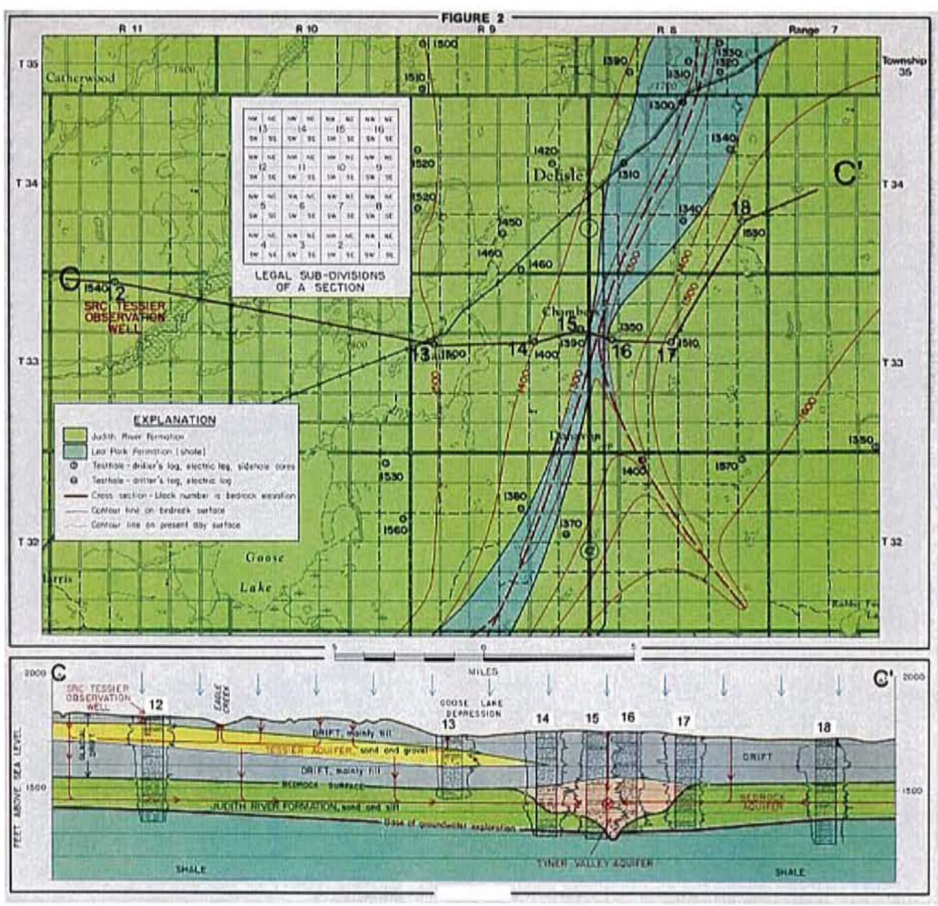


Fig. 38a. Cross section C-C' showing the hydrogeology of the Tyner valley and Tessier aquifers (Meneley *in* Christiansen et al. 1970).

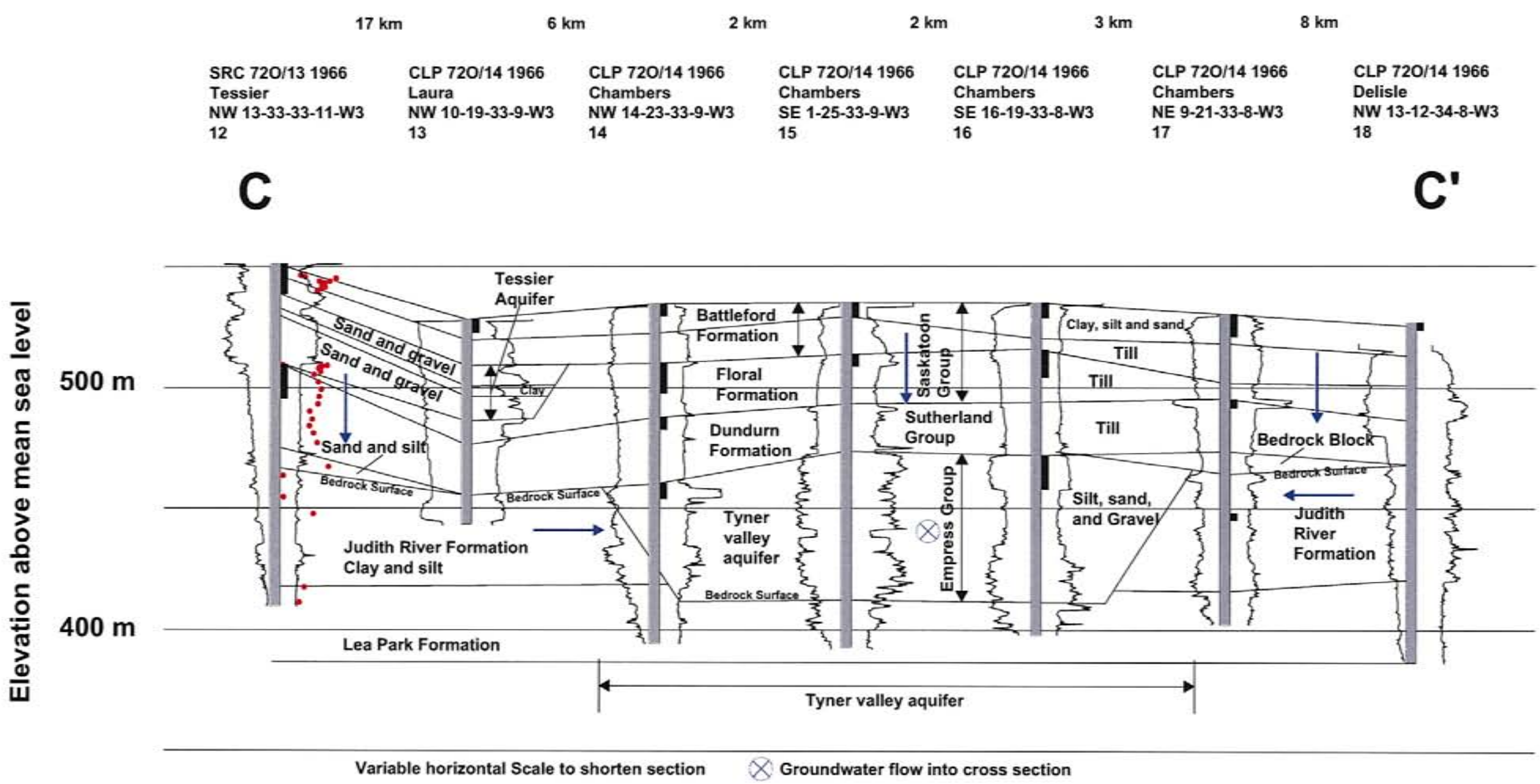


Fig. 38b. An update of cross section C-C' showing stratigraphy of the Tyner valley and Tessier aquifers and the groundwater flow system (Meneley *in* Christiansen et al. 1970). Arrows show the direction of groundwater flow. See Fig. 37 for the location of cross section.

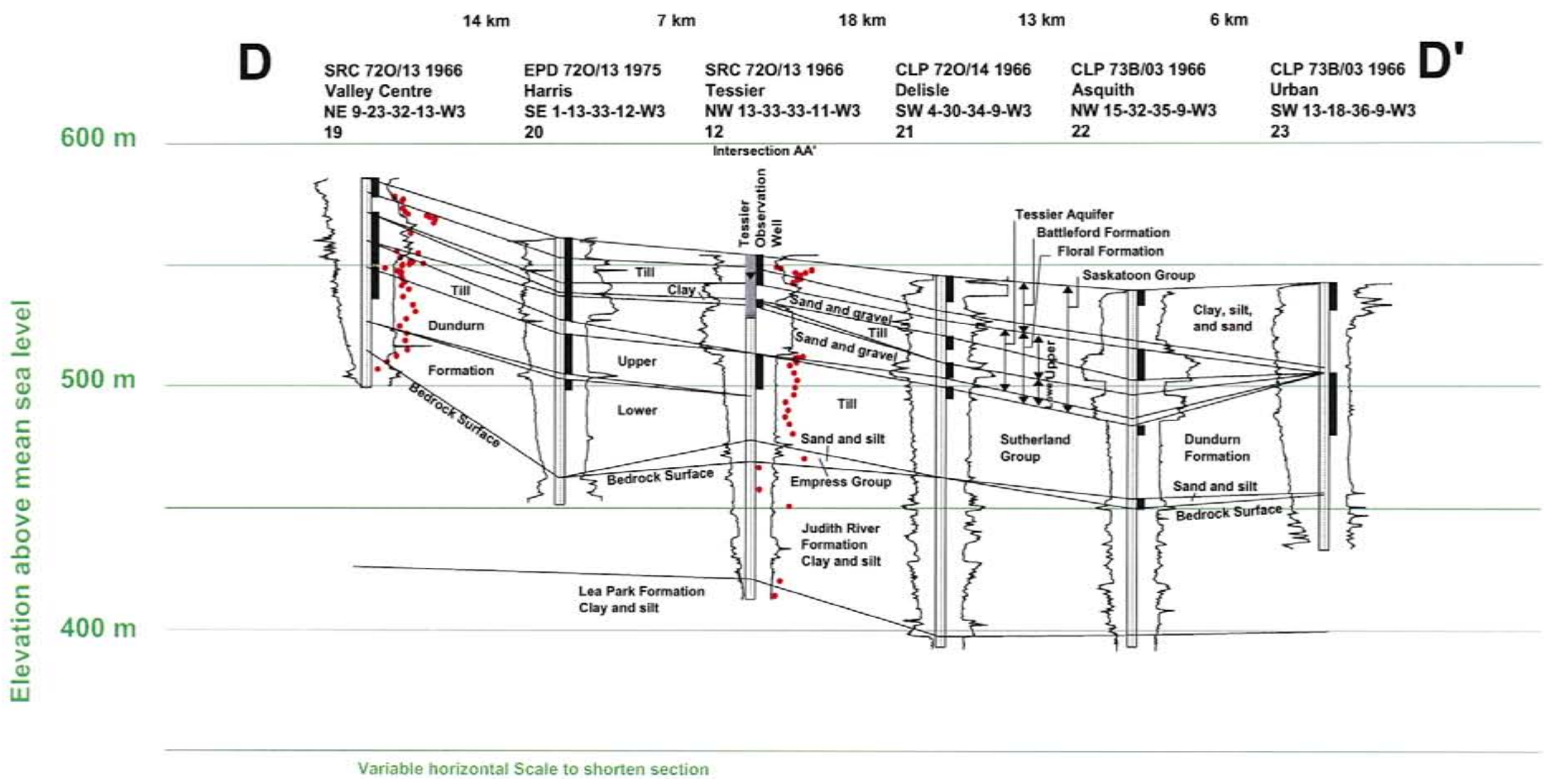
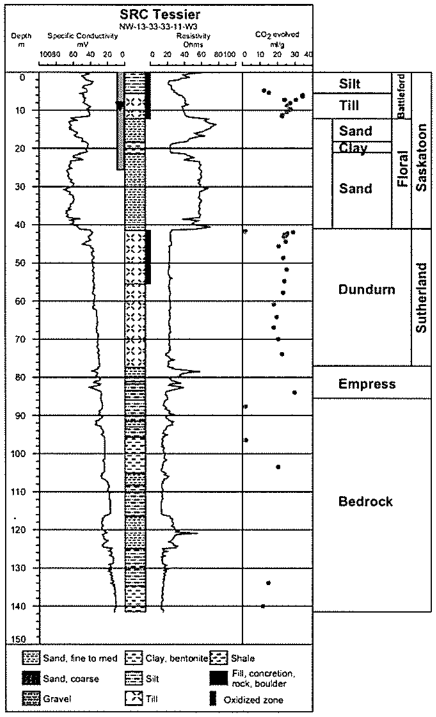
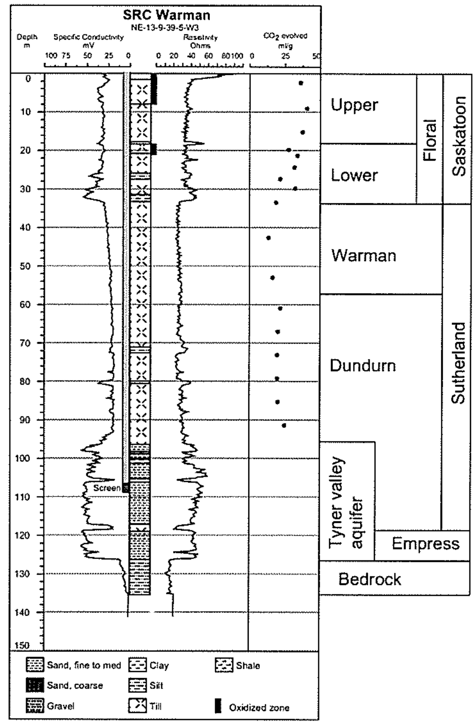


Fig. 39. Cross section D-D' showing the Tessier aquifer and observation well completed in the lower unit of the Floral Formation. See Fig. 37 for the location of cross section.



Constituent	ppm		
Hydroxide as OH	Nil	pH	7.35
Carbonate as CO_3	Nil	**Concentration**	**1350**
Bicarbonate as HCO_3	449	Conductivity (uS/cm)	1520
Sulphate as SO_4	**548**	**Hardness as $CaCO_3$**	**788**
Chloride as Cl	11	Alkalinity as $CaCO_3$	368
Calcium as Ca	172		
Magnesium as Mg	88	Date of analyses:	
Sodium as Na	72	June, 1970	

Fig. 40. Tessier observation well completed in the Tessier aquifer (Figs. 37-39). A chemical analysis is included with the concentration, hardness, and sulphate constituents high-lighted.



Constituent	ppm		
Hydroxide as OH	Nil	pH	7.70
Carbonate as CO_3	Nil	**Concentration**	**2269**
Bicarbonate as HCO_3	690	Conductivity (uS/cm)	2490
Sulphate as SO_4	**840**	**Hardness as $CaCO_3$**	**539**
Chloride as Cl	82	Alkalinity as $CaCO_3$	539
Calcium as Ca	132		
Magnesium as Mg	51	Date of analyses:	
Sodium as Na	458	November 22, 1965	

Fig. 41. Warman observation well (Fig. 34(B)) completed in glacial sand of the Dundurn Formation. A chemical analysis is included with the concentration, hardness, and sulphate high-lighted.

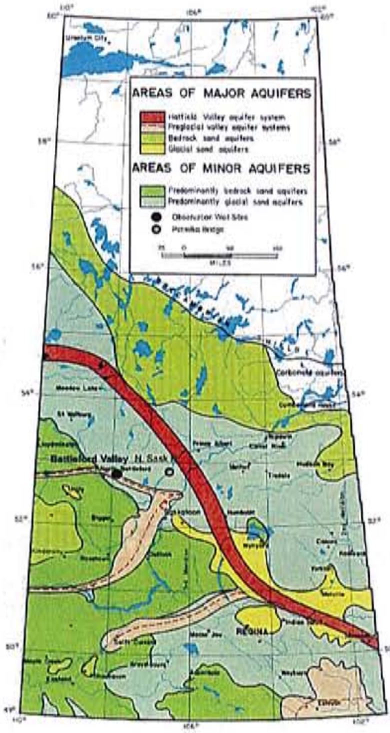


Fig. 42. Brochure of southern Saskatchewan (Christiansen et al. 1970) showing the location of major and minor aquifers, Battleford valley aquifer, and the Lilac observation well, and Petrofka bridge sites.

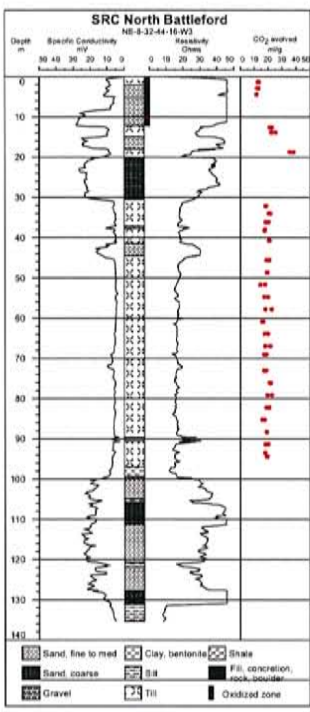
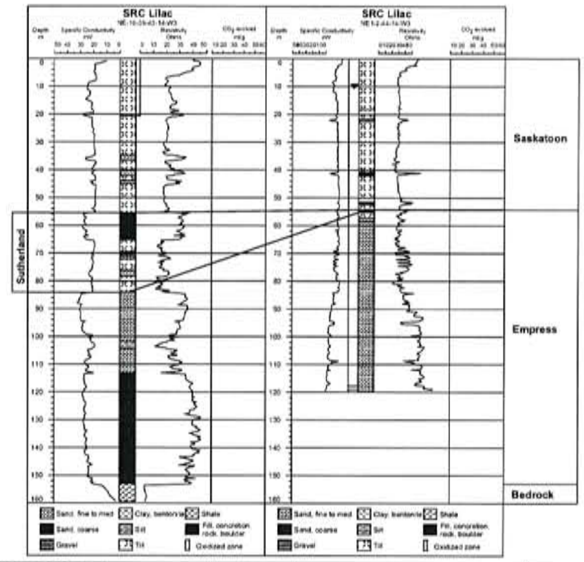


Fig. 43. Borehole log showing the hydrogeology of the Battleford valley aquifer.



Constituent	ppm		
Hydroxide as OH	Nil	pH	7.80
Carbonate as CO_3	Nil	**Concentration**	**1188**
Bicarbonate as HCO_3	604	Conductivity (uS/cm)	1400
Sulphate as SO_4	**276**	**Hardness as $CaCO_3$**	**522**
Chloride as Cl	10	Alkalinity as $CaCO_3$	495
Calcium as Ca	131		
Magnesium as Mg	47	Date of analyses:	
Sodium as Na	108	August 10, 1970	

Fig. 44. Lilac observation well completed in glacial sand of the Empress Group and a borehole log to bedrock about 300 m from the well along Highway 40. A chemical analysis is included with the concentration, hardness, and sulphate constituents high-lighted.

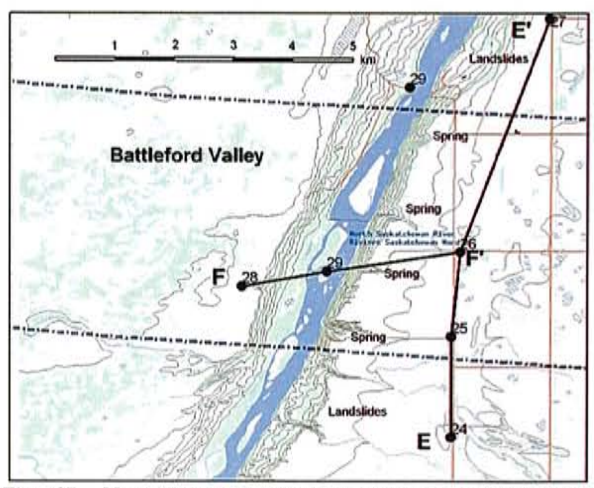


Fig. 45. Map showing location of cross section E-E' across the preglacial Battleford valley aquifer east of the North Saskatchewan River valley.

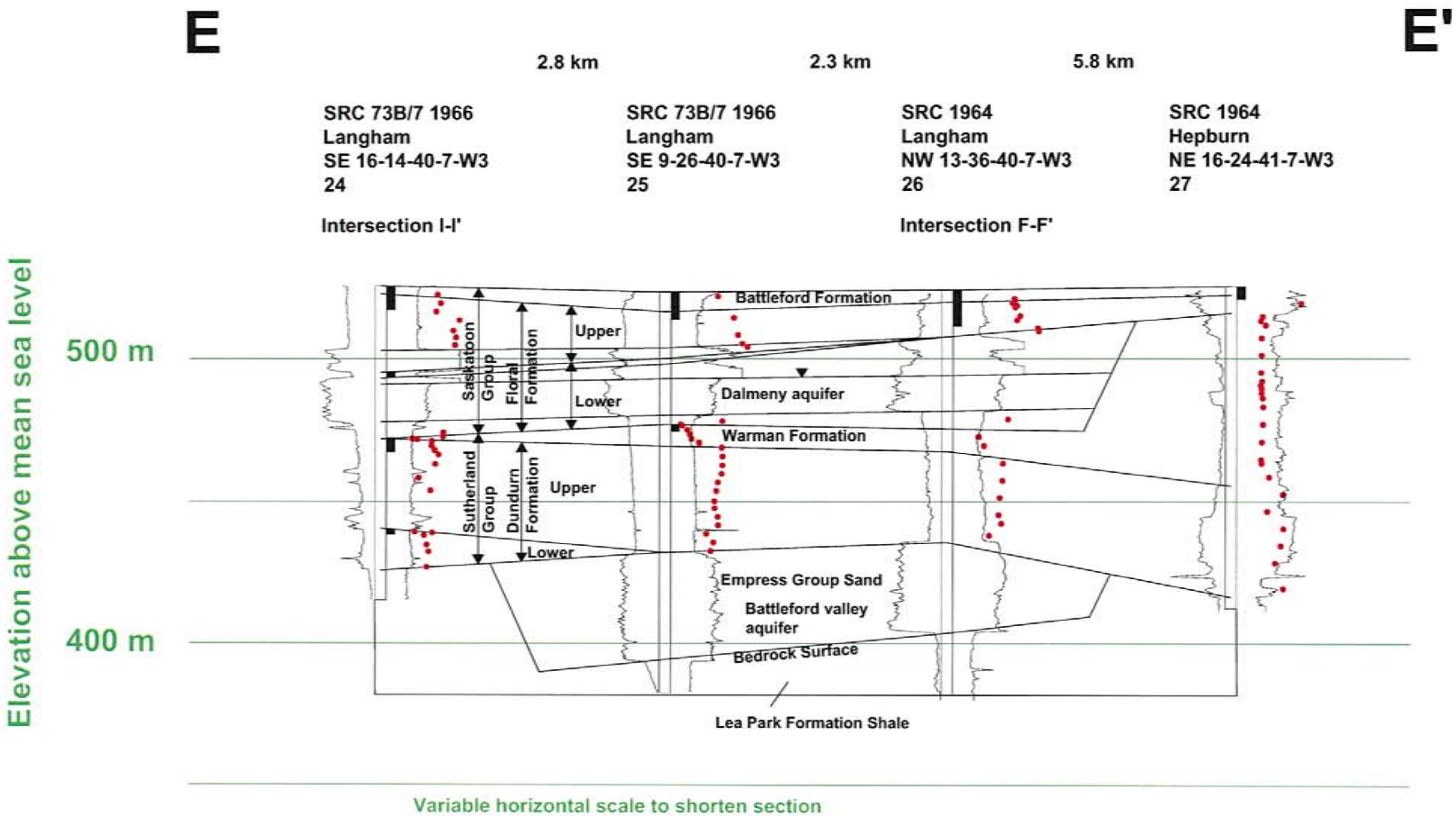


Fig. 46. Cross section E-E' across the Battleford valley aquifer. See Fig. 45 for location of cross section

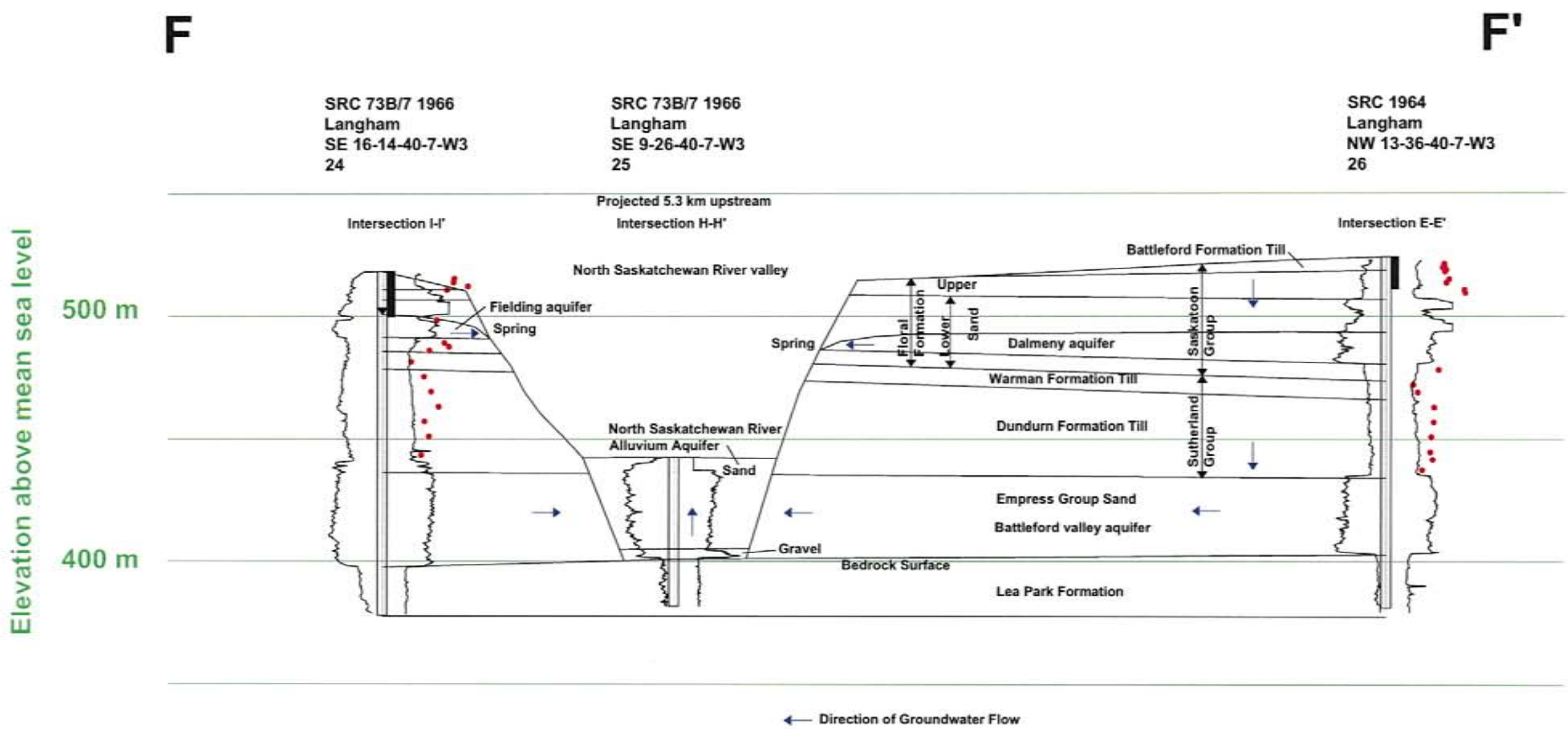


Fig. 47. Cross section F-F' across the North Saskatchewan River valley and along the Battleford valley aquifer northwest of Saskatoon (Fig. 34) showing the Battleford valley aquifer discharging groundwater into the North Saskatchewan River alluvium aquifer.

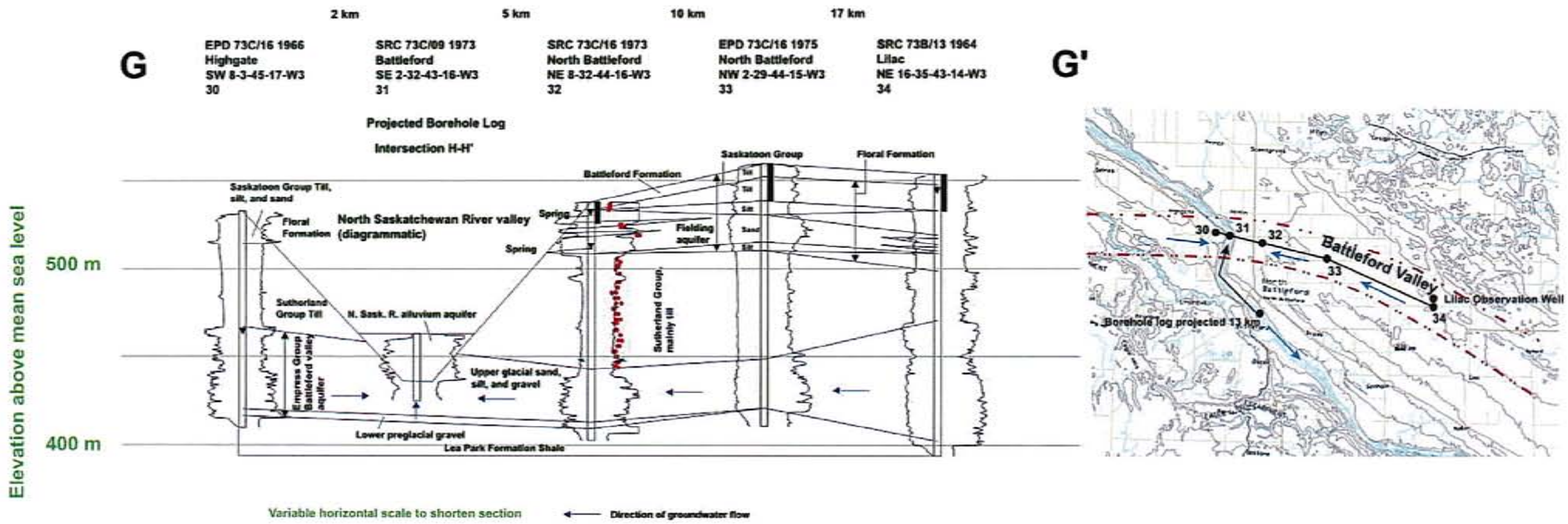


Fig. 48. Longitudinal section G-G' crossing the North Saskatchewan River valley at North Battleford (G-G', borehole log 31) showing the Battleford valley aquifer discharging groundwater into the North Saskatchewan River valley alluvium aquifer.

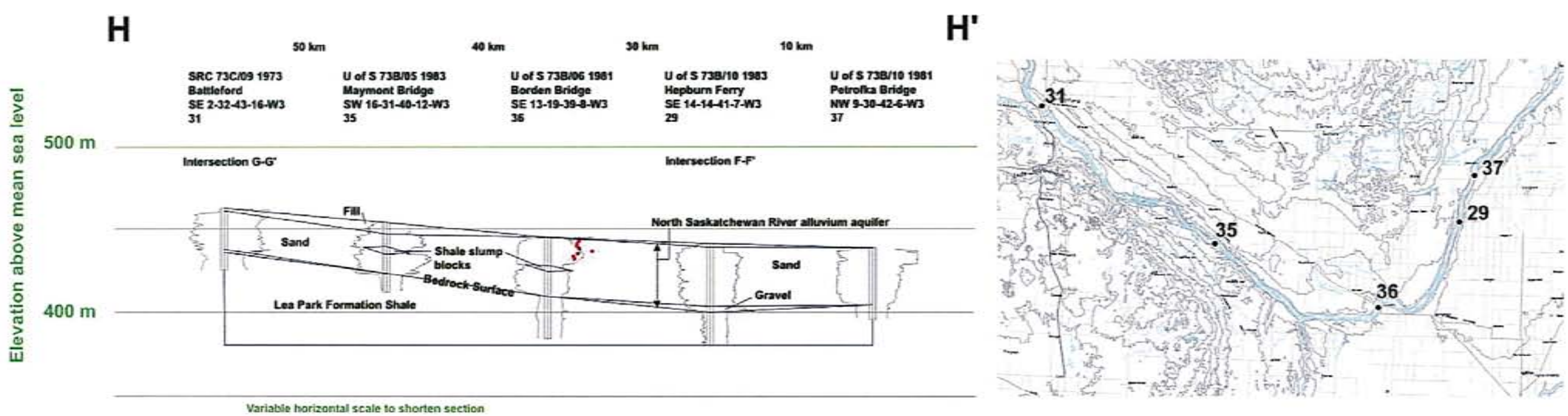


Fig. 49. Longitudinal section H-H' showing the North Saskatchewan River alluvium between Battleford and Petrofka bridge.

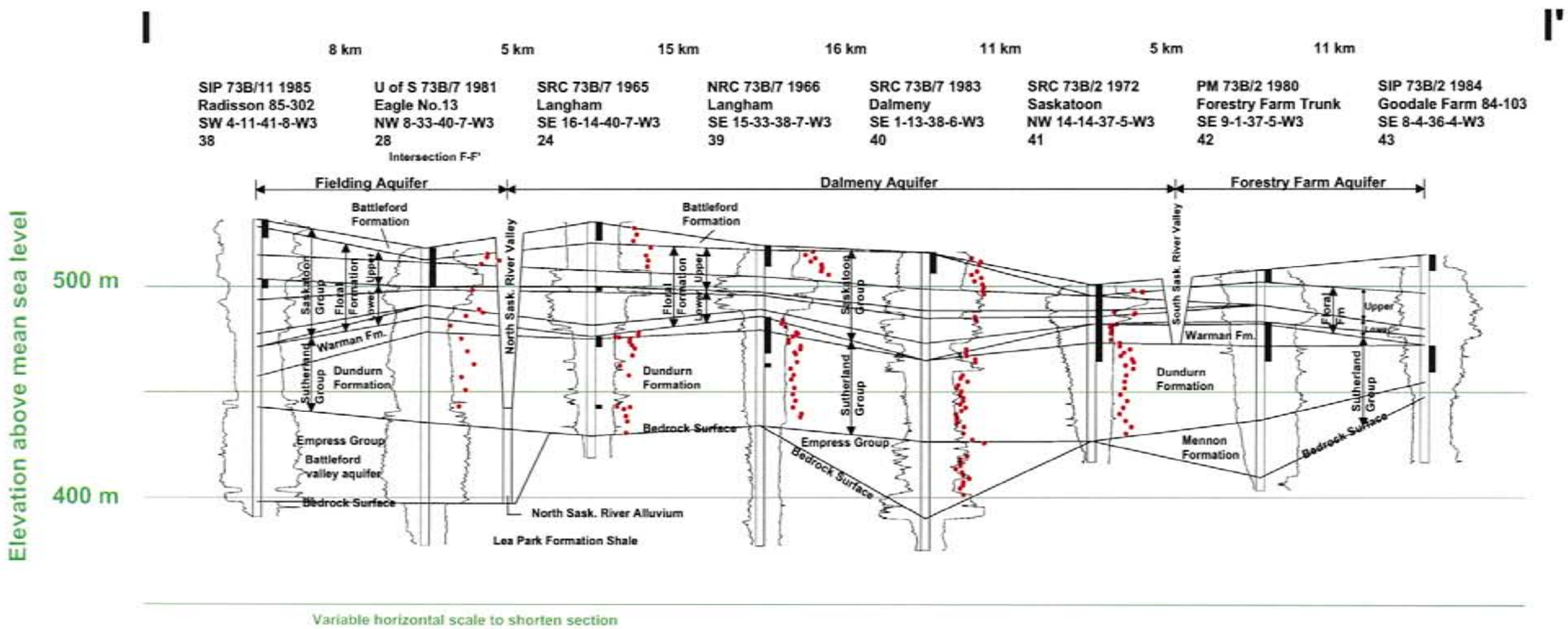


Fig. 51. Cross section I-I' through Fielding, Dalmeny, and Forestry Farm aquifers showing groundwater discharge to the North and South Saskatchewan river valleys.

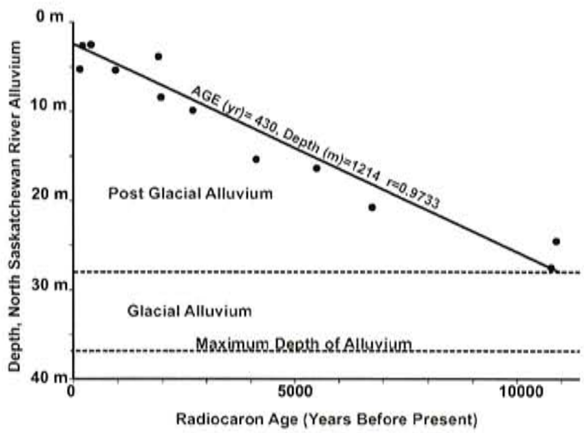
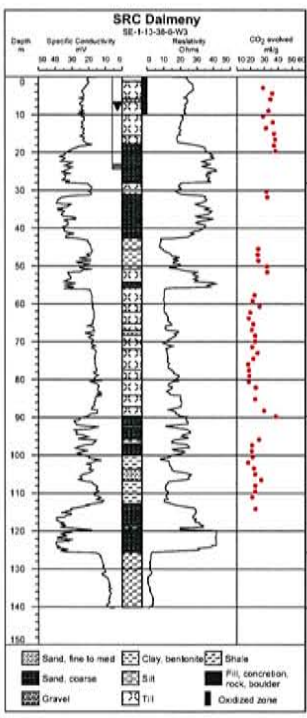


Fig. 50. Relationship between depth and age of North Saskatchewan River alluvium (Christiansen, 1983).



Constituent	ppm		
Hydroxide as OH	Nil	pH	6.90
Carbonate as CO_3	Nil	**Concentration**	**2637**
Bicarbonate as HCO_3	709	Conductivity (uS/cm)	2500
Sulphate as SO_4	**1255**	**Hardness as $CaCO_3$**	**1656**
Chloride as Cl	11	Alkalinity as $CaCO_3$	581
Calcium as Ca	358		
Magnesium as Mg	182	Date of analyses:	
Sodium as Na	98	June 21, 1968	

Fig. 52. Dalmeny observation well completed in the upper sand of the Dalmeny aquifer (Fig. 51). A chemical analysis is included with the concentration, hardness, and sulphate constituents high-lighted.

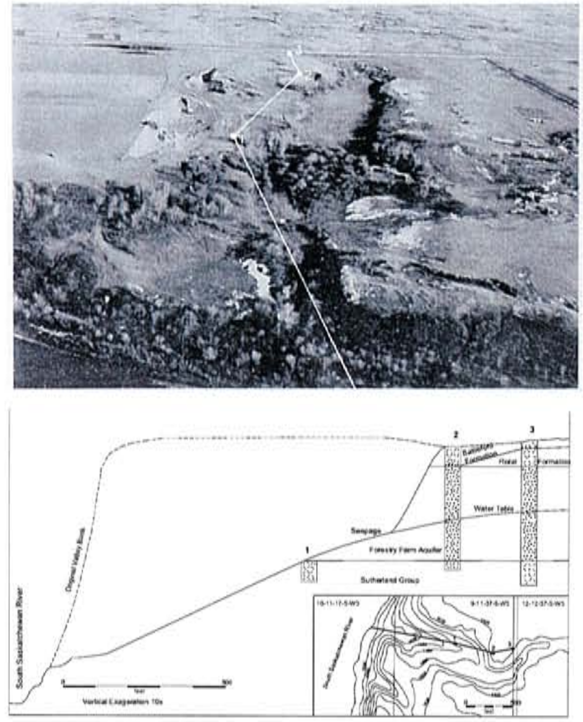


Fig. 53. Petursson's Ravine formed by spring sapping or piping of sand from the east bank of South Saskatchewan River about 2 km north of the intersection of Attridge Drive and Central Avenue, Saskatoon. From Christiansen and Meneley (1970, Fig. 46, p. 52).

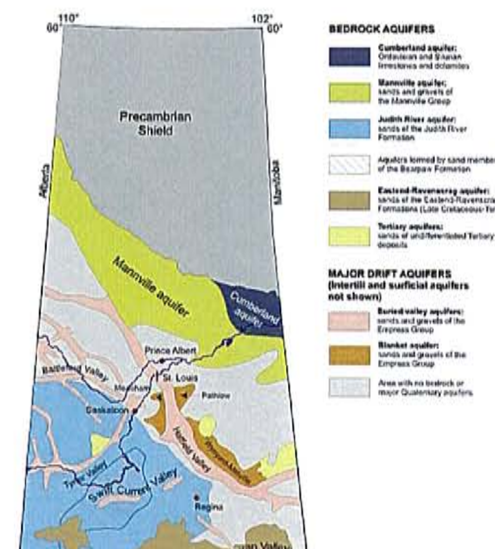


Fig. 54. Major aquifers in Saskatchewan yielding potable water by H. Maathuis, Saskatchewan Research Council showing the location of the St. Louis bridge site over the Hatfield valley.