The effects of glaciations upon karst landforms and groundwater flow systems in Canada

Derek Ford

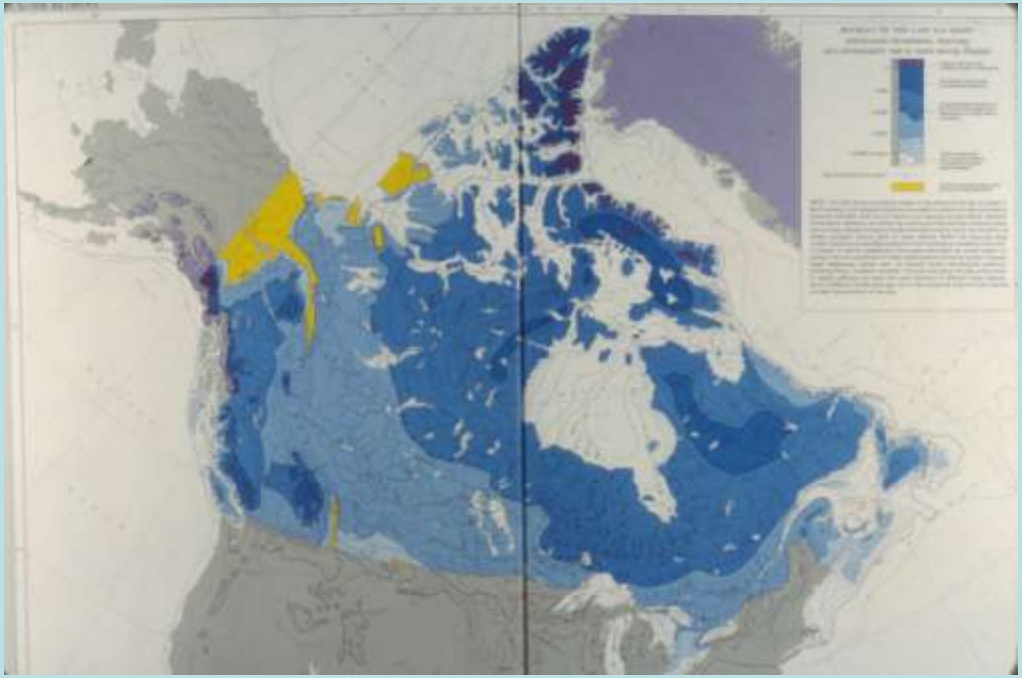
If the Creator had consulted me in the Beginning
I would have recommended something simpler.

Alfonso of Castile,

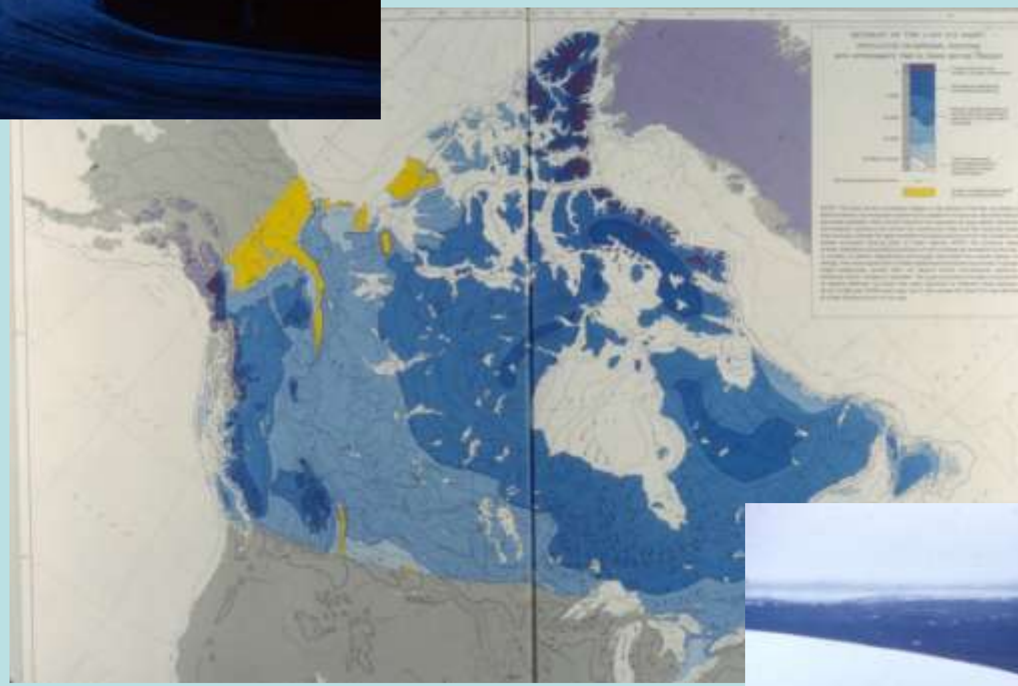
16th century

The number ofexensive glaciations in the Northern Hemisphere is not firmly established but there have been at least five during the past 2.5 Ma (the Quaternary).

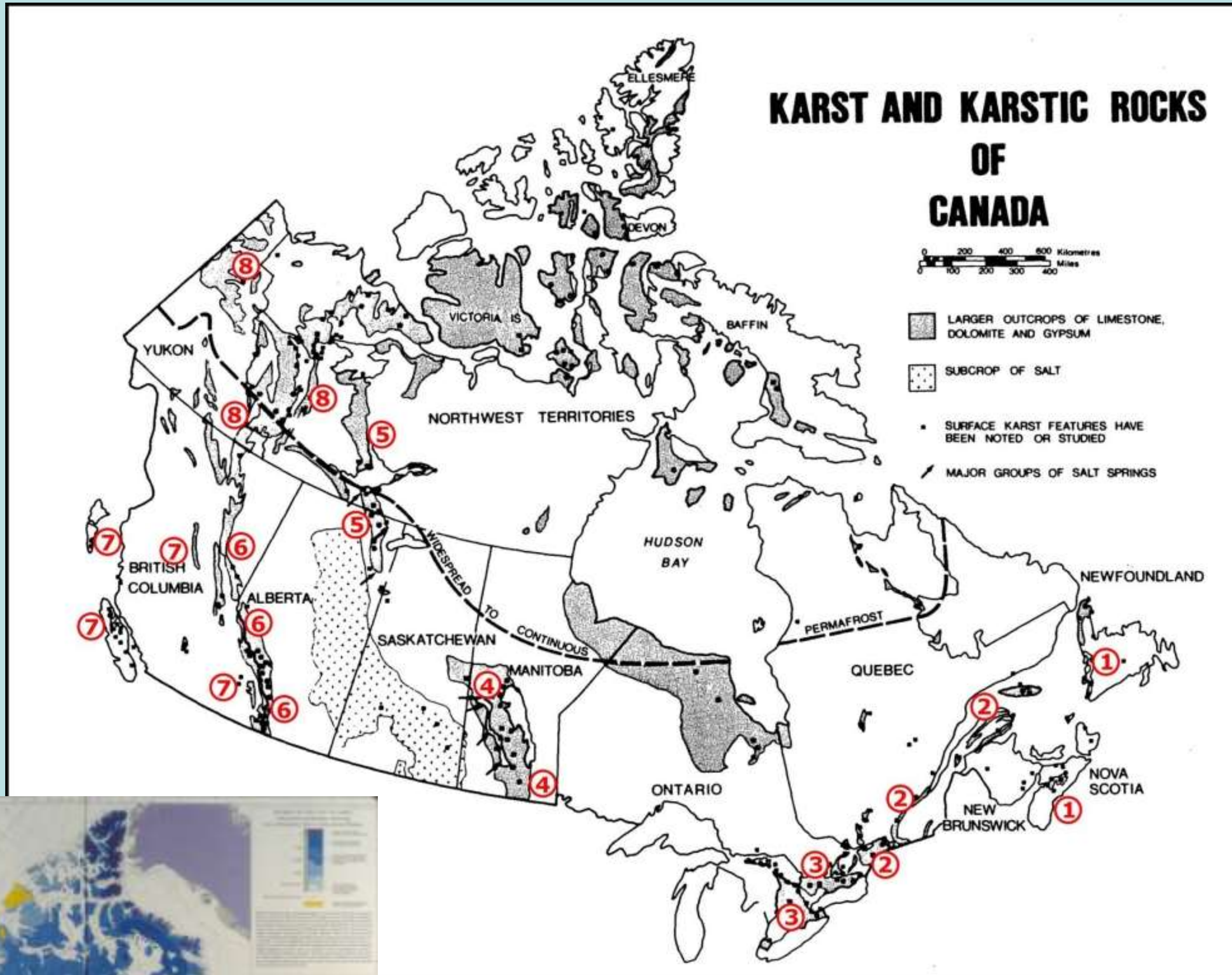
Canada was covered by a mixture of alpine valley glaciers, ice caps and the mighty ‘Laurentide’ continental ice sheet.

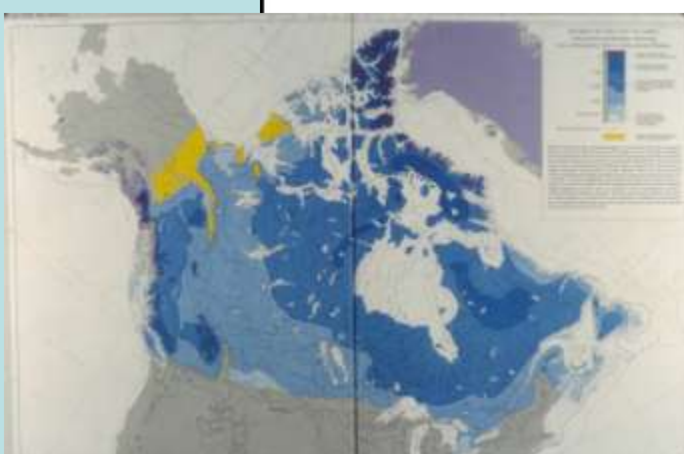


The western ‘Cordilleran’ ice sheet consists of coalescent valley glaciers. Ice thicknesses are up to 2000 m.



The Laurentide Ic Sheet has two centres and submerges most of the topography east of the western cordillera. Modeled ice thicknesses are up to 5000 m.





The ‘outcrop’ of limestone, dolomite and gypsum in Canada is approximately 900,000 sq km, but much of it is buried by local glacial debris. The ‘subcrop’ of Prairie salt is ~400,000 sq km.

Classification of the effects of glaciation on karst

destructive
- -erase
- -dissect
- -infill
- -inject

inhibitive

preservative

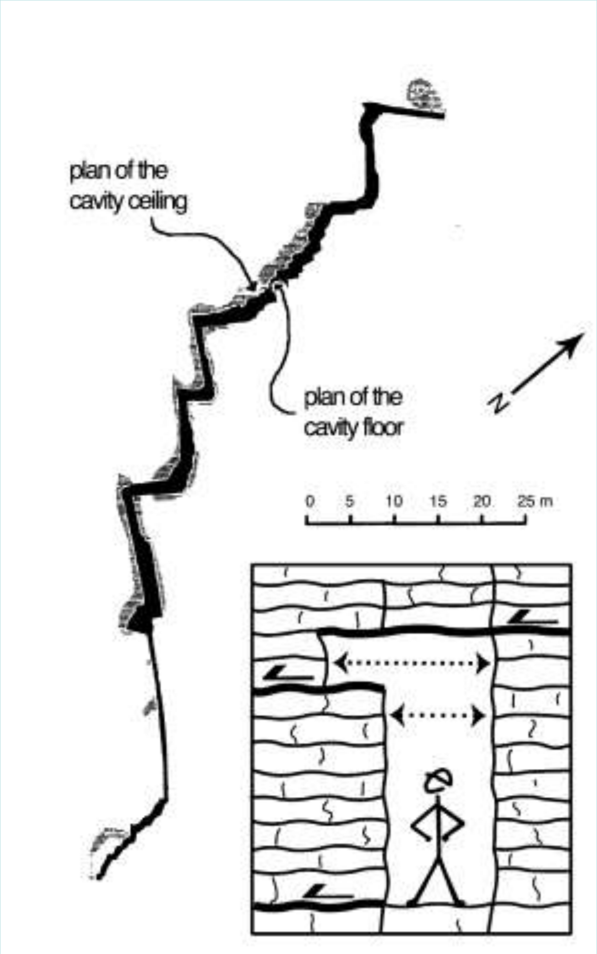
stimulative
- -raise the head
- -lower the springs
- -flex and pump

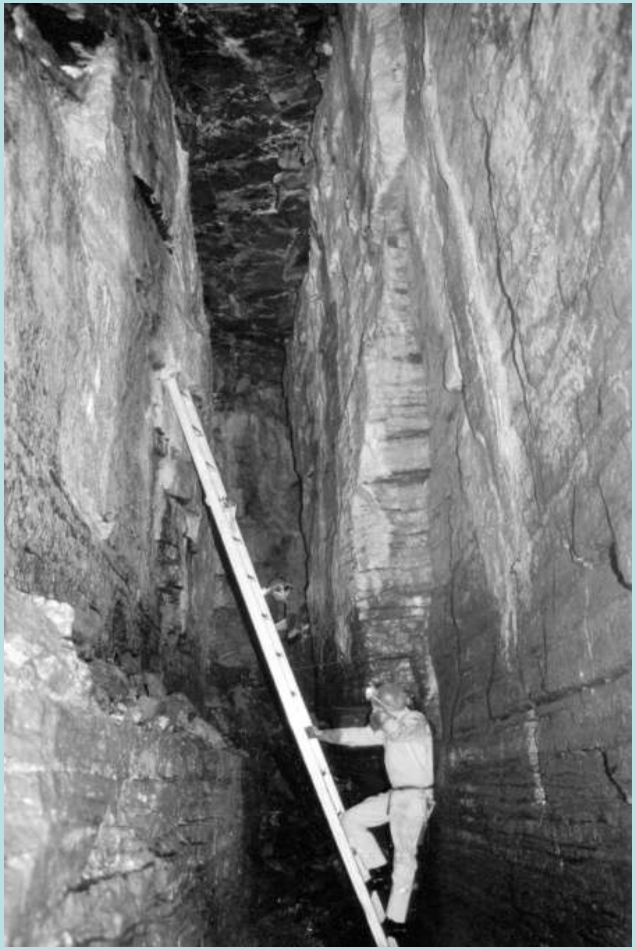
initiating

From Ford 1983. *Journal of Hydrology*, 61(1/3);149-158.

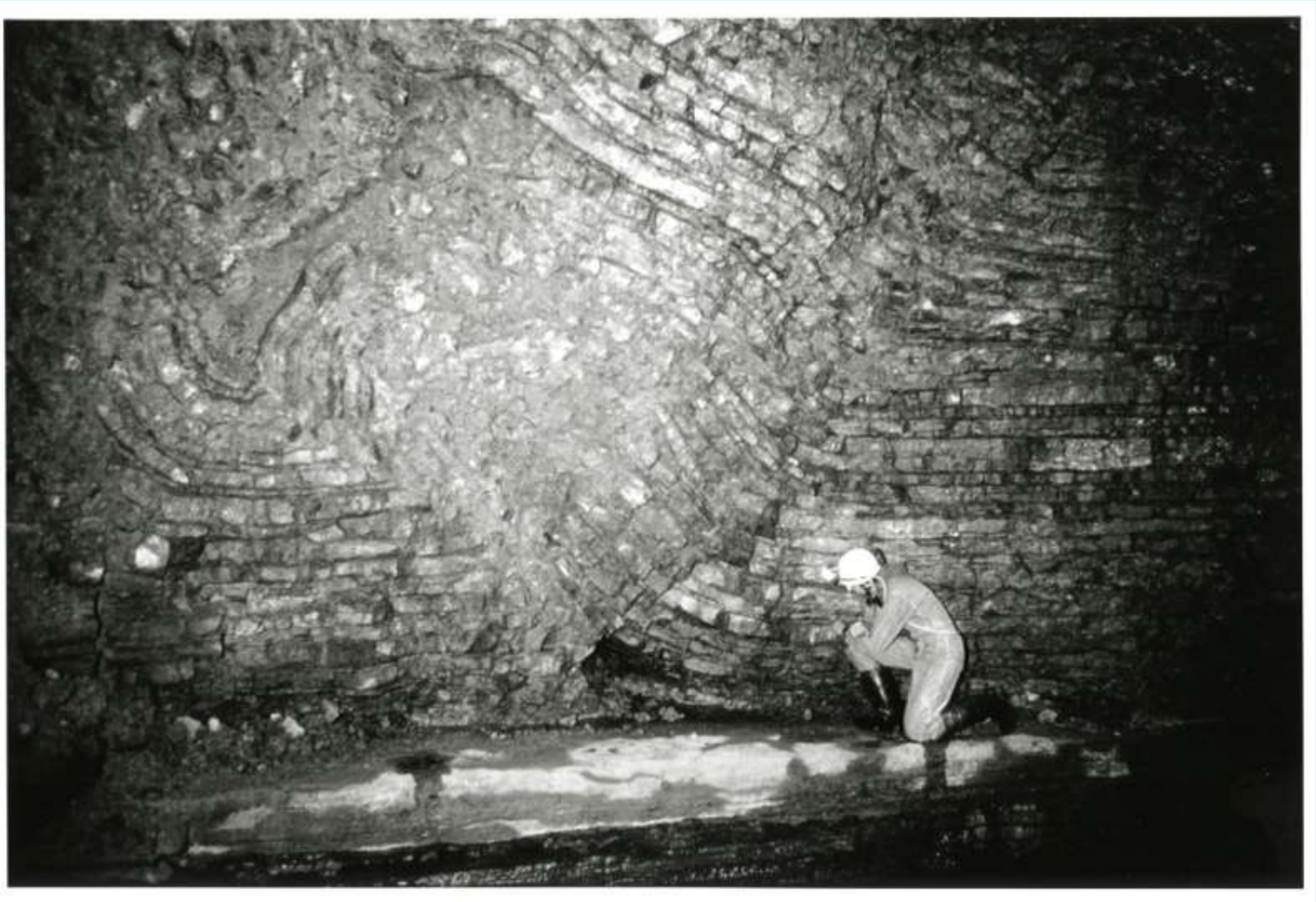
Erase and deform

Where a glacier is 'cold' at its base (i.e. below the pressure melting point of ice) it may freeze to the underlying bedrock and drag it by glacier flow.





This is an example of simple displacement at shallow depth in thick to massive strata (i.e. mechanically strong) in Montreal.



Thinner limestone beds were drag-folded at this site near Quebec City.
Note that glacial till is injected into the core of the fold.

Where a glacier is 'temperate' (i.e. is at the pressure melting point at its sole) it slides on a thin film of pressure melt water, and can behave like a giant bulldozer. This the more common mode of glacier flow seen at the Canadian karst sites I have investigated

The typical glacier will remove just the top one or two beds of any epikarst in one given glacial cycle or stade of advance.

This is an excellent example of ‘beheaded’ epikarst preserved under one-two metres of glacial till near Hamilton.

Glacial scour on the stoss face and freeze-thaw plucking on the lee have converted a small doline into an inverted roche moutonnee at this site at Castleguard.


Sub-glacial calcite precipitation by solution-freeze.



Glacial dissection of mountainous karst

Rivers can be swallowed underground, creating caves and karst aquifers. Glaciers cannot be swallowed and so may dissect the underground system by cirque and U-valley entrenchment.

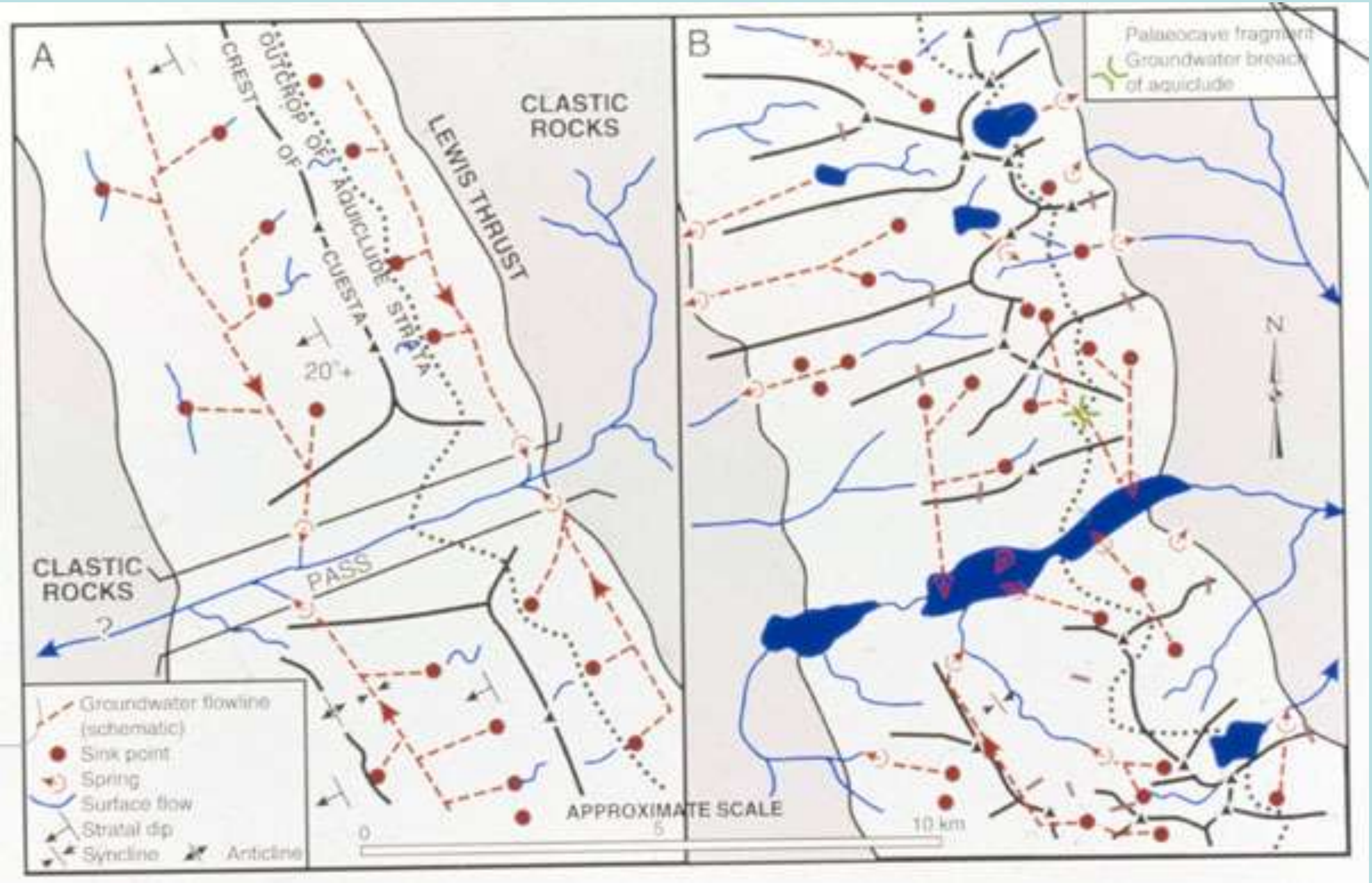
Glacial dissection is common in the Alps. The great example in Canada is around Crowsnest Pass in the Rockies.

(see Ford, 1983. Alpine karst systems at Crowsnest Pass, Alberta-British Columbia. *Journal of Hydrology*, 61(1/3); 187-192).

Fragments of relict caves are found up to 1400 m above the cirque and valley floors.

Cave and karst aquifer development continue today, with major regional springs discharging from phreatic passages at the floor of the Pass.

The first example of a magnetically reversed speleothem (i.e. older than 780,00 years BCE) was collected from a relict phreatic gallery at the arrow, 90 m above the floor of the Pass.

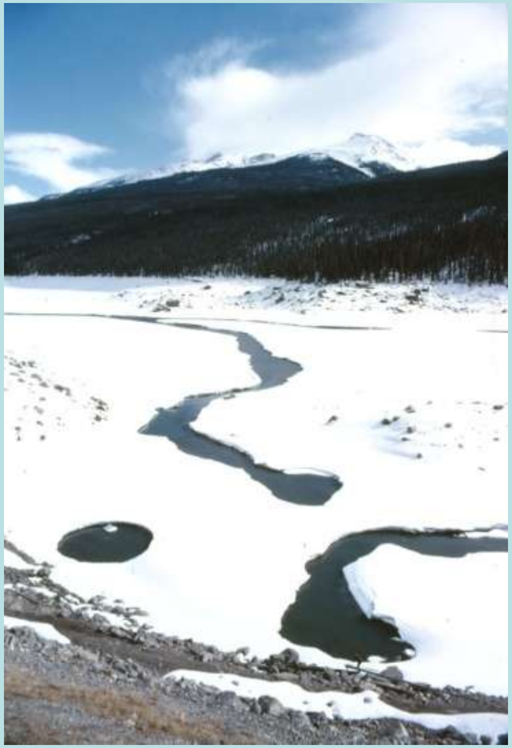


Two distinct aquifers, one above a shaly aquitard and one below it, have been dissected by glacial cirque and valley entrenchment.

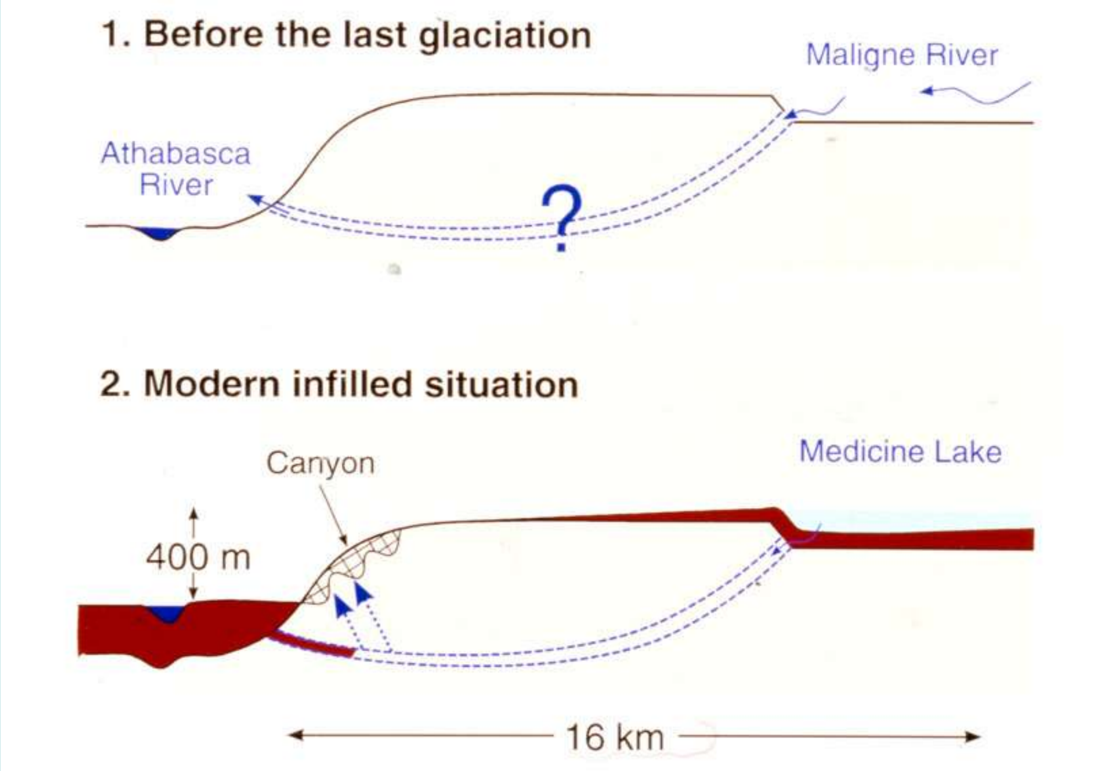
Infilling – karst topography can be buried and groundwater flow disrupted by infilling the recharge landforms (dolines or sinkholes) with glacial detritus and/or burying the springs.

The example on the left is of a doline in gypsum at sea level in Nova Scotia that has been sectioned by coastal wave attack. On right, a doline on a high ridge on Vancouver Island, filled by glacial sands and now partially emptied by suffosion into the aquifer.

The Maligne River system in Jasper National Park is one of the greatest examples of infill at both the sink and the springs. Scenes above show the upper basin and the River before it sinks at Medicine Lake.
On right; Medicine Lake filled and overflowing, seen from its upstream end.

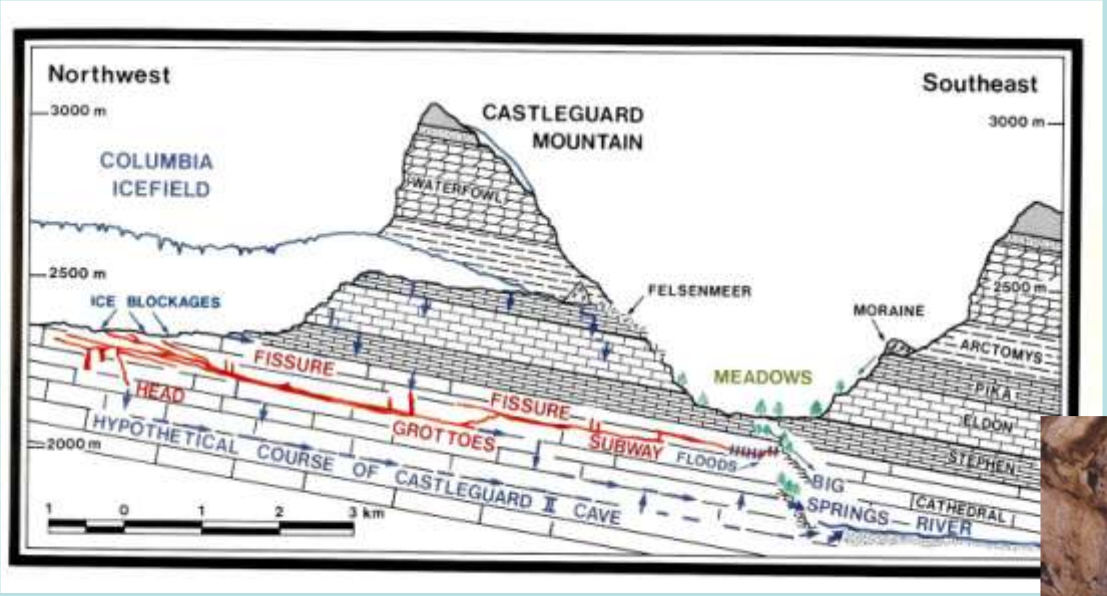


Above; Medicine Lake half full, seen from the summer overflow channel. Its basin is 6 km in length, 1-2 km wide. The water sinks into a landslide pile directly behind the photographer.
On right; at the end of winter the Lake has shrunk to a pond a few hectares in area, drained underground through its floor.



The model for the Medicine Lake system.The straight-line underground flow route is 16 km long, with a modern headfall of ~400 m. The water resurges via >60 separate springs in Maligne Canyon and below, clear evidence that a great cave system has been aggraded at its downstream end. Dye traces take 80 hours to pass through in low flow, only <u>eleven hours </u>at high stage.

Injection – **where hydraulic gradients are high and there is abundant meltwater, glacial detritus may be injected deep into an aquifer, clogging it.**

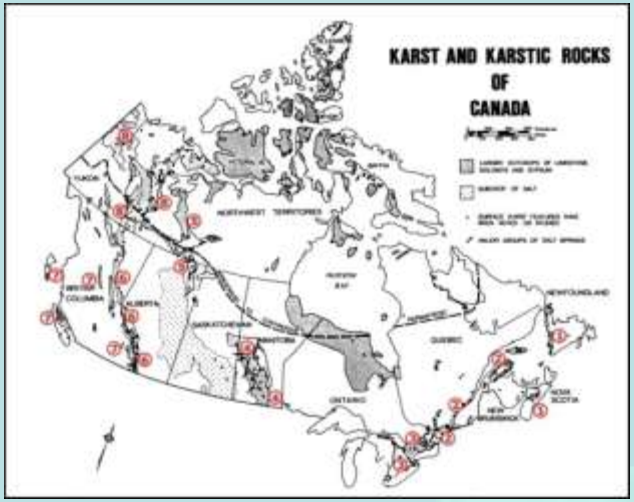


Castleguard Cave terminates under the modern Columbia Icefield in the Rockies. Several of its passages are filled with glacier ice itself.

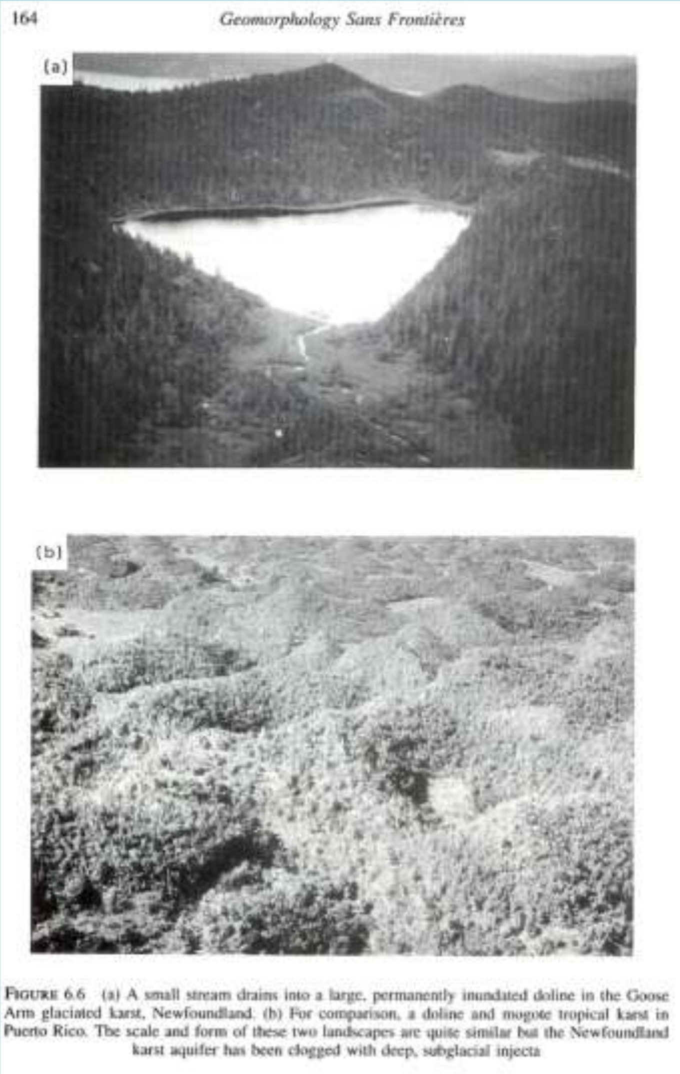
On left; sub-glacial high pressure injection of boulders has filled the entrance to a passage, now exposed by recent glacier retreat.

On right; an entrance filling of till seen from the inside

On left: during the last glaciation, Nakimu Caves in the Selkirk Mountains, B.C., were almost completely filled with sub-glacial debris, beginning with a diamicton (in this case, the fluviatile sliding bed deposit shown here) and fining upwards through sands and silts to varved clays (below).
Post-glacial stream action has removed much of the fill at Nakimu but other caves can remain plugged.



The Bonne Bay Karst, ,Newfoundland, Is different again. There is ~300 m of local relief in steeply Dipping limestones and dolomites, with glaciated valleys but also distinct ‘pepino’-like hills. Large and small sinkholes are ponded.

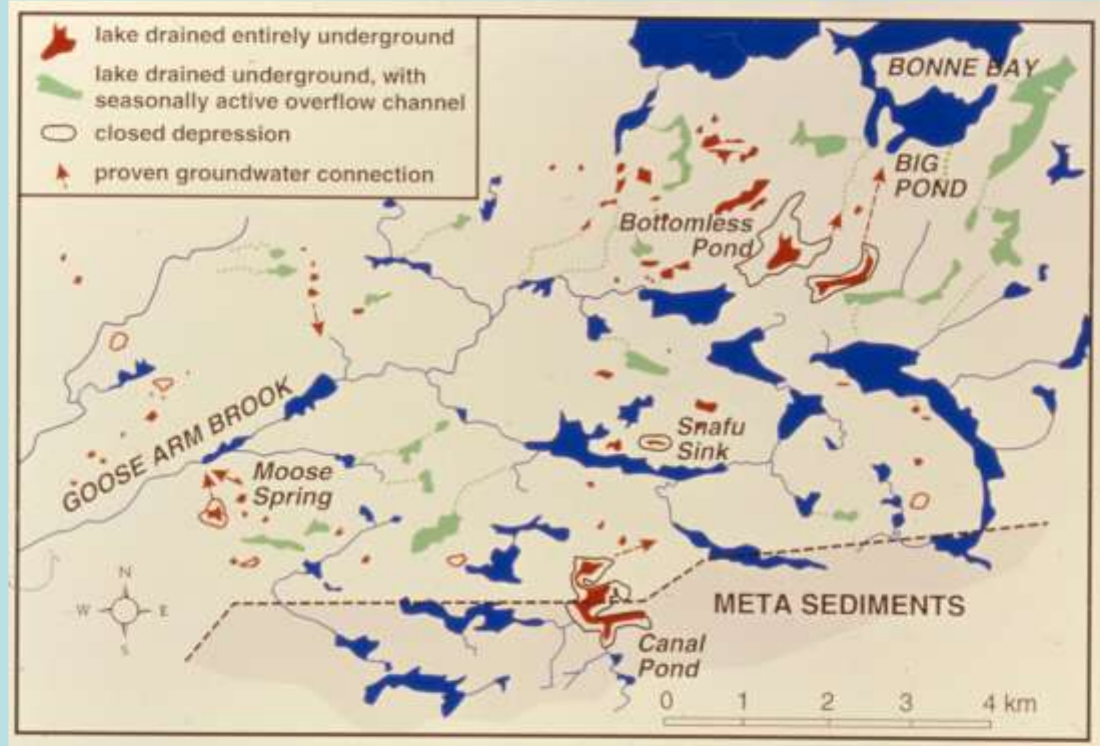

164 Geomorphology Sans Frontières

(a)

(b)

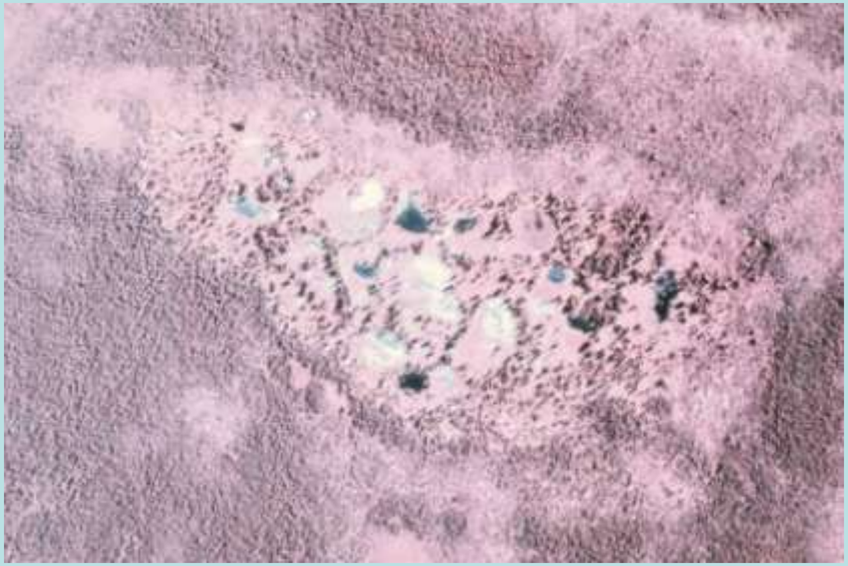
FIGURE 6.6 (a) A small stream drains into a large, permanently inundated doline in the Goose Arm glaciated karst, Newfoundland. (b) For comparison, a doline and mogote tropical karst in Puerto Rico. The scale and form of these two landscapes are quite similar but the Newfoundland karst aquifer has been clogged with deep, subglacial injecta

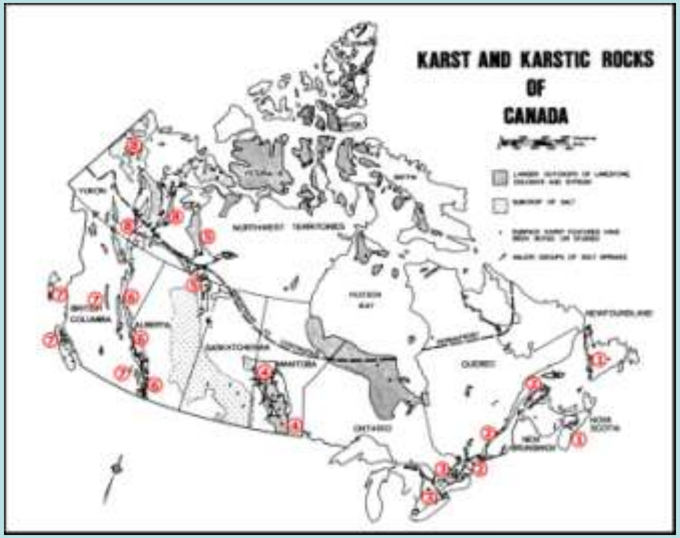
Karolyi, M.S., and Ford, D.C. The Goose Arm Karst, Newfoundland, *Journal of . Hydrology*, 61(1/3);. 181-6.

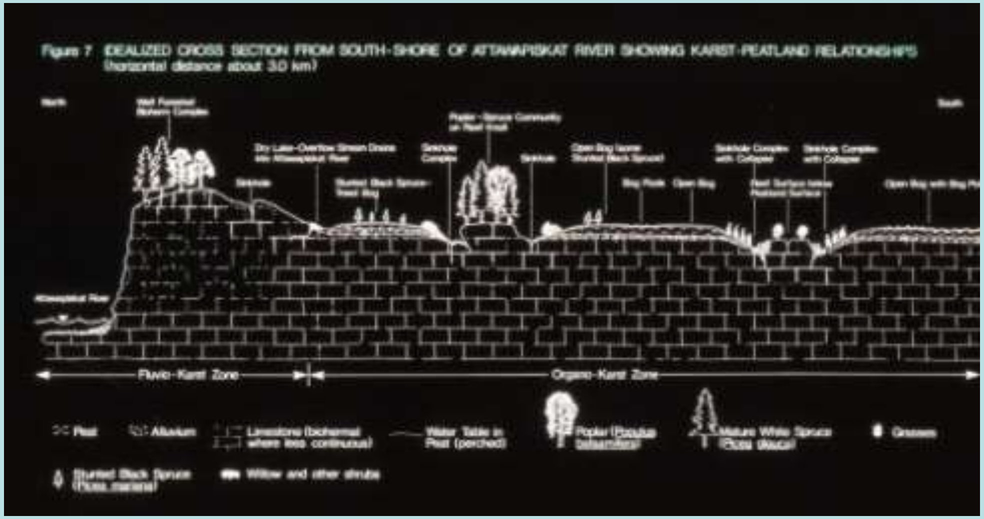


The region is interpreted as a Jamaican-style cockpit karst that was scoured by ice and subject to injection of glacial clays that disrupted mature conduit aquifers. As a result, some sinkholes drain always underground, some drain only by surface overflow, and others display melt season overflow only.

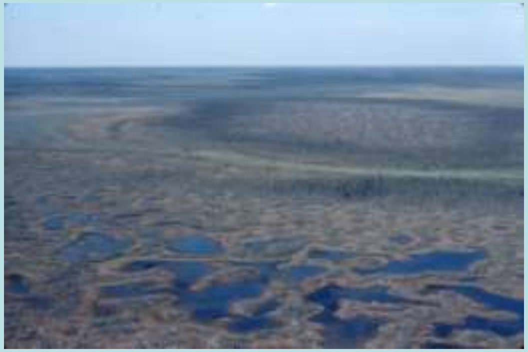
Inhibitive – the presence of glacial debris rich in soluble fragments of limestone, gypsum, etc. protects the karst bedrock underneath from post-glacial dissolution. 1-2 m of till is often sufficient to protect limestones and dolomites entirely. 40 cm of marl is good enough in some sites.





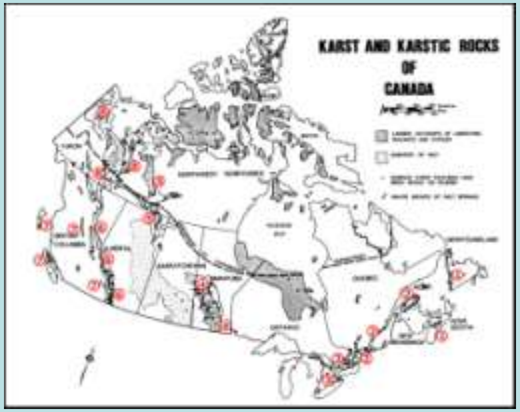


Inhibitive – Attawapiskat Karst, James Bay

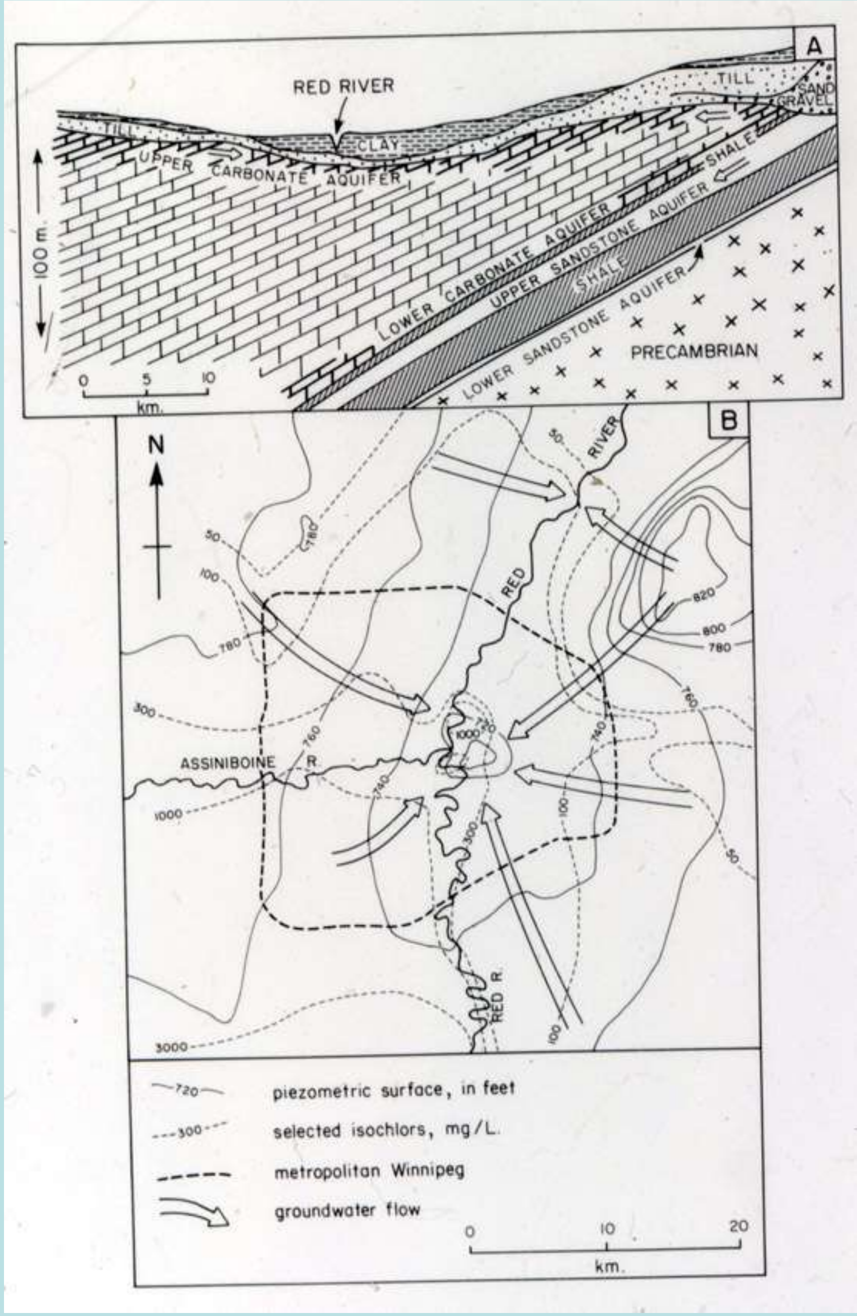


Glacial and marine sediments on a plain with vey low hydraulic gradients protect underlying limestones except where regional river entrenchments allow karst flow from sinkpoints in projecting coral reefs.

Preservative – in a few places the basal Laurentide Icesheet was 'cold', i.e. it froze to the bedrock and protected it without significant drag displacement of the rock because ice flow occurred only in the plastic ice above the base.



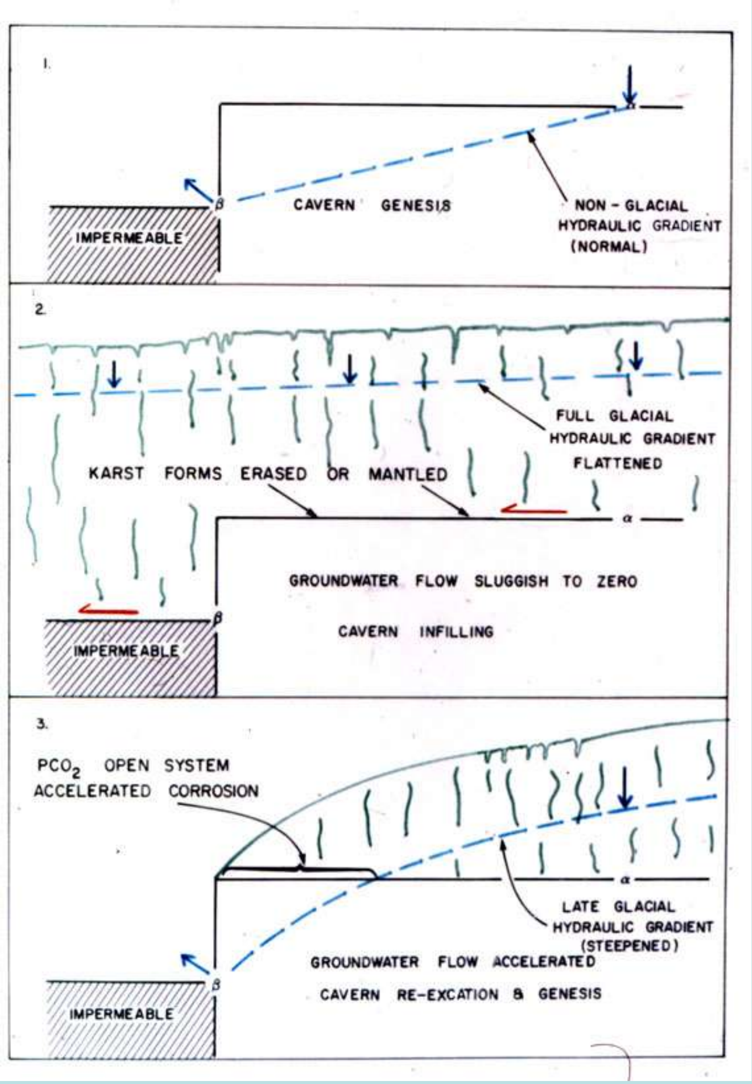
The great example is Winnipeg, where 400 square kms of dolomite karst pavement is preserved under melt-out tills and glacial lake clays (the 'Glacial Lake Agassiz Plain'. Because of the freezing there was little injection of debris into the epikarst and it forms a fine protected aquifer. (Ford, 1983. The Winnipeg Aquifer, *Journal of Hydrology*, 61(1/3); 177-180).

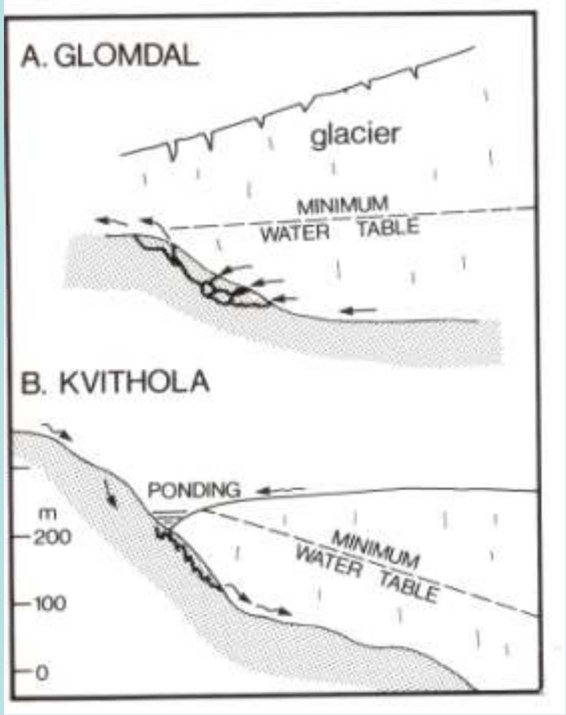


Above – the protected epikarst preserved on higher ground at the edge of the city. Note the thick, buffering till overlay.

Left – the epikarst is very extensive And up to seven metres in depth. Basal limestone and sandstone aquifers are contaminated by salt, which overpumping has drawn in to wells in the centre of the city.

Stimulate – (1) by focussing flow and/or raising the hydrostatic head

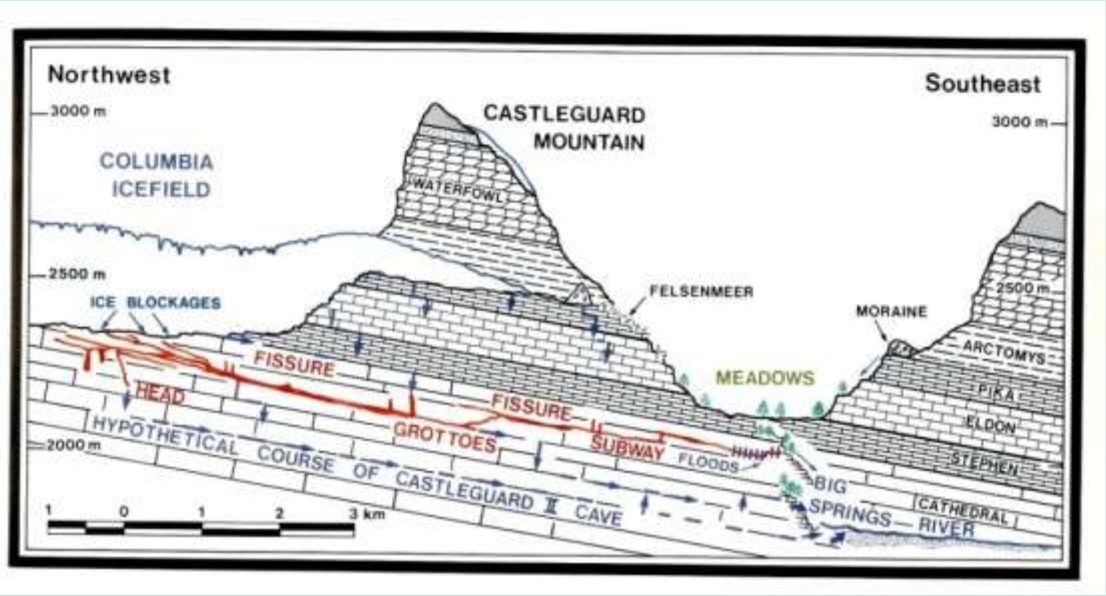




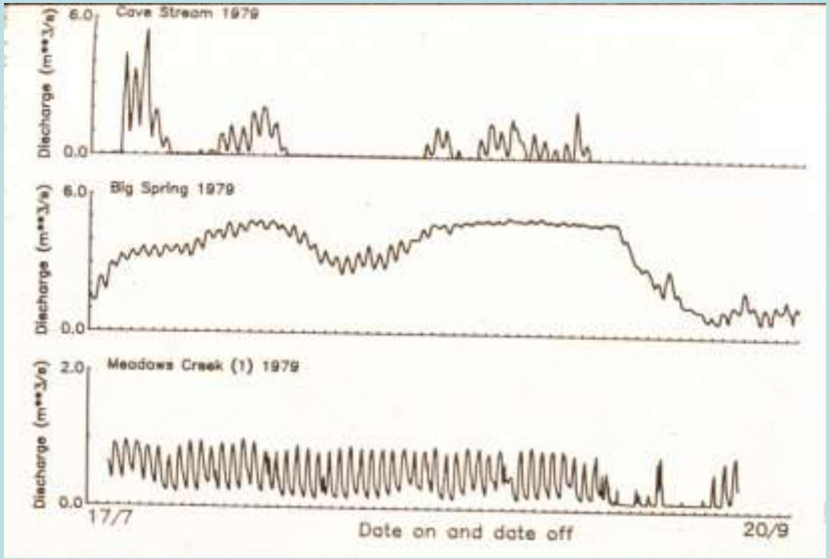
The karst aquifer may be subordinate to the glacier aquifer, or *vice versa.* Perched or focussed meltwater can create conduits very rapidly.

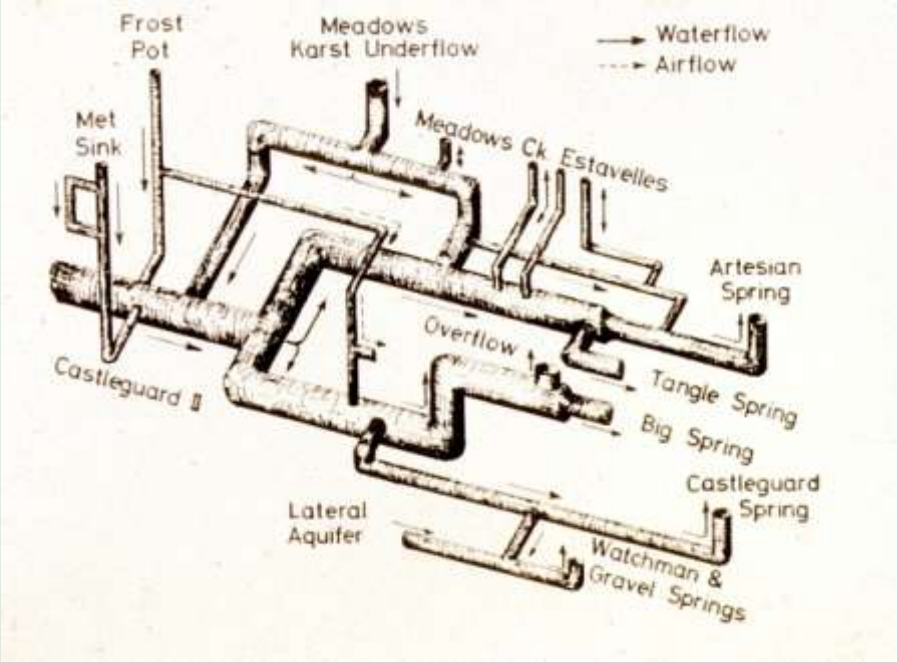
Above – examples from S-E. Lauritzen, Norway.

Around the Columbia and Mons icefields
in the Canadian Rockies



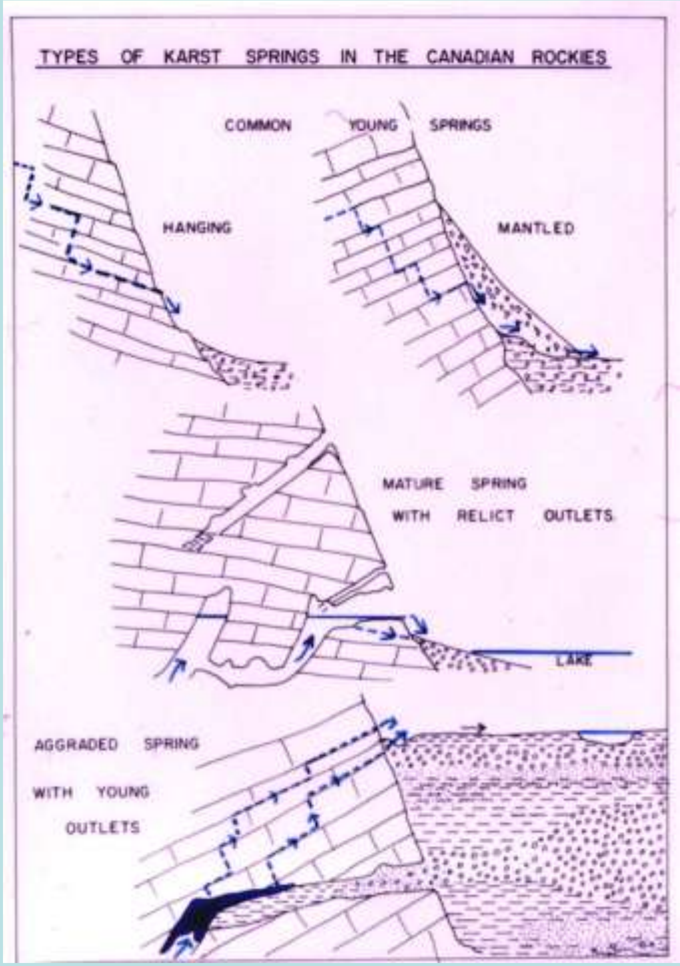
The Castleguard karst is our greatest canadian example of stimulation.
The highest melt season overflow spring is >350 m above the elevation of the winter springs.



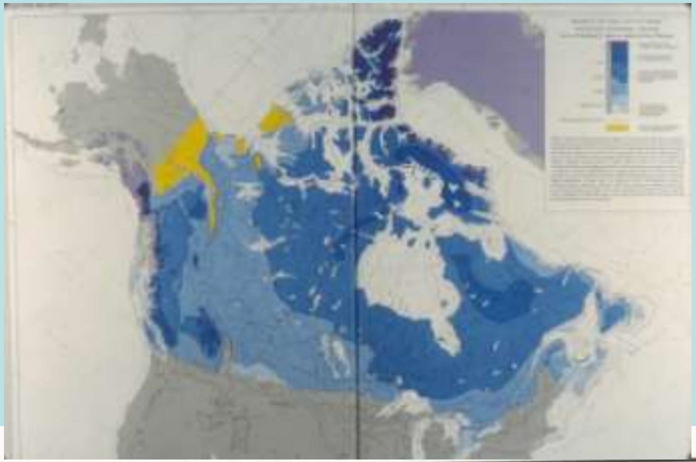


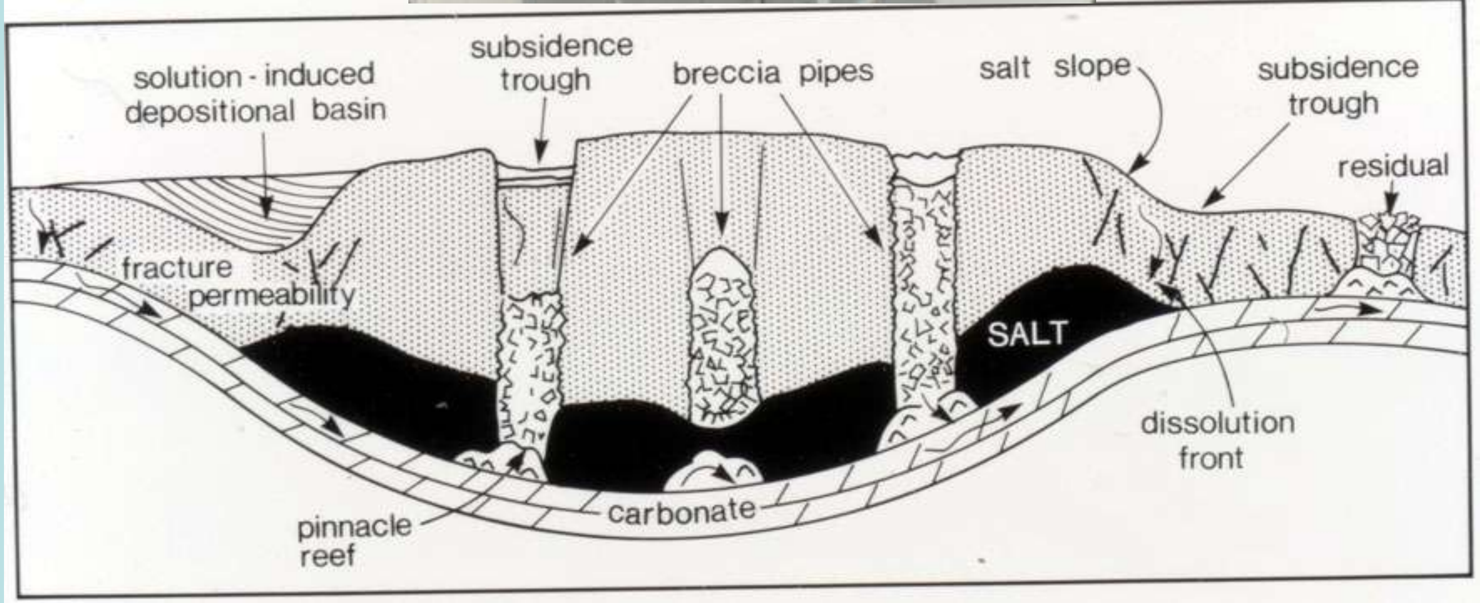
Proportional model of the modern Castleguard aquifer, based on discharge, chemical and isotopic analysis.

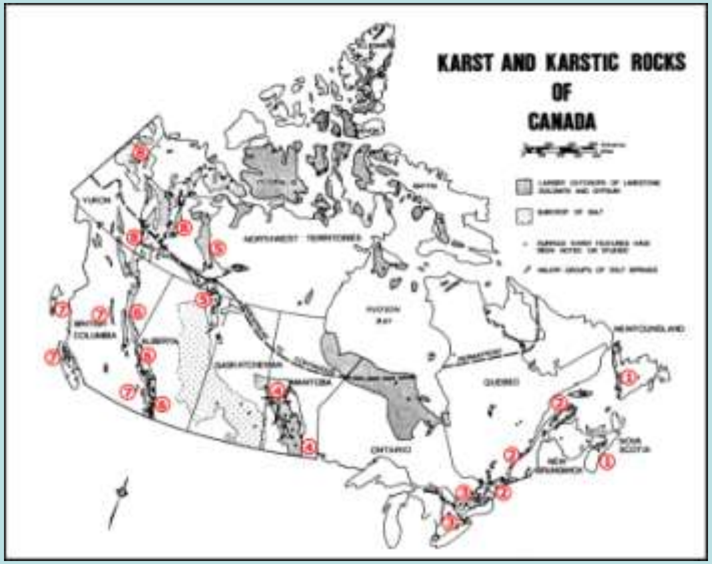
Stimulate – (2) by entrenchment that lowers the springs or leaves them hanging.



Flex and pump – as the Laurentide Icesheet is receding and the crust is rebounding in the presence of abundant meltwater. Imagine the effect of loading 3000-5000 m of the Laurentide Continental Icesheet onto Sedimentary strata and then unloading them!







The Elk Point salt (Paleozoic) is at 200-2000 m beneath Mesozoic clastic rocks of low permeability that may fracture under glacial isostatic release.

Above – the Elk Point Salt subcrop in Manitoba, Saskatchewan and Alberta.

Left – a Toth-type model of basin flow in the sedimentary rocks.

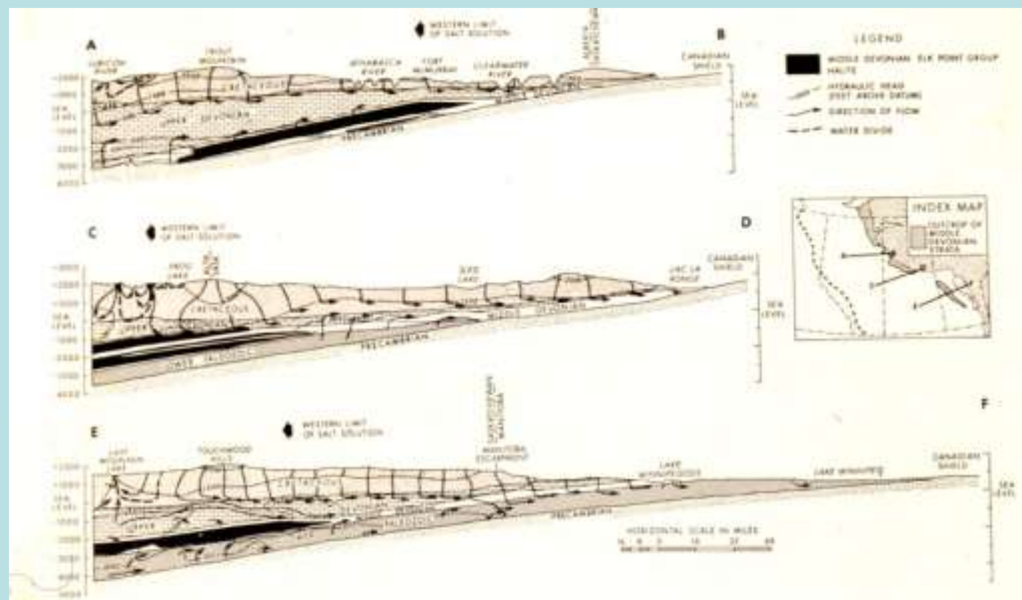
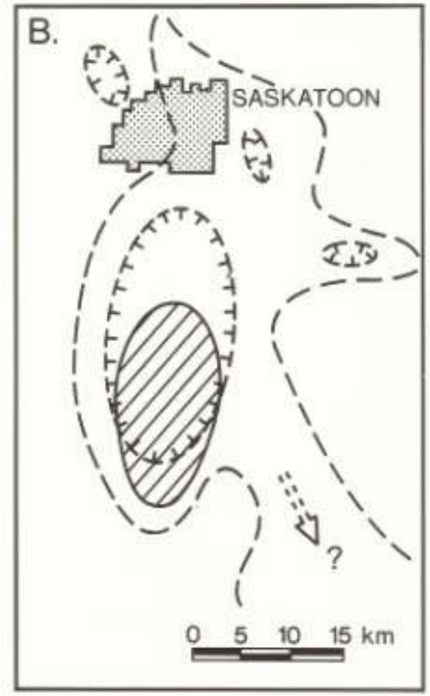
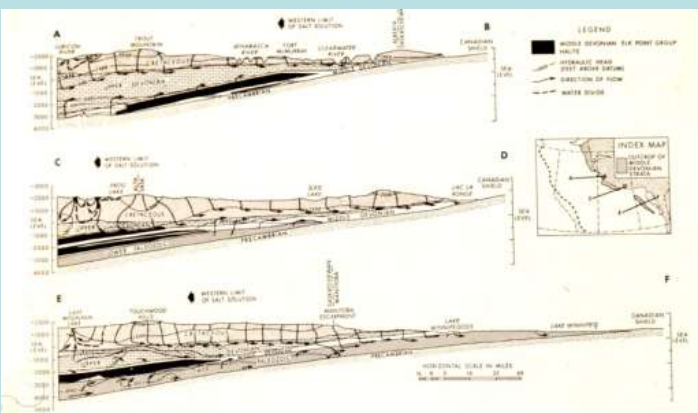


Fig. 3. Hydraulic head cross sections showing distribution of fluid flow in relation to solution of Middle Devonian Elk Point group halite, southern par
western Canada sedimentary basin.



Late glacial collapse structures and salt springs in the Prairie Provinces



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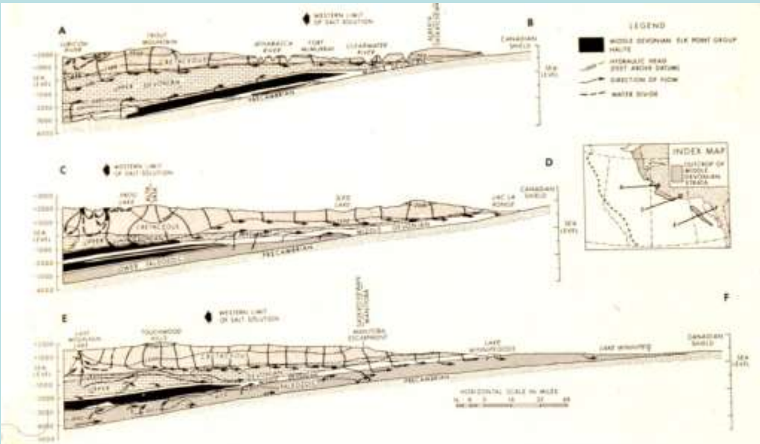

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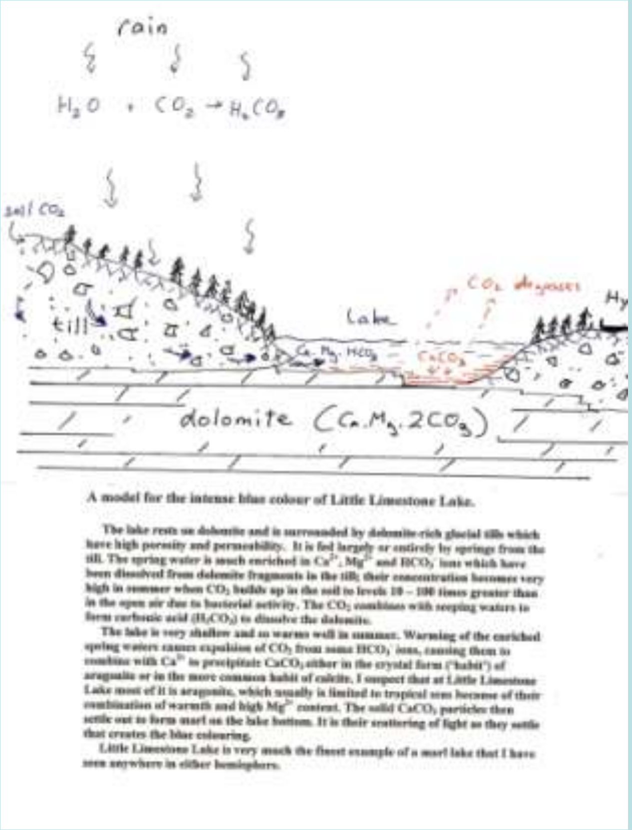
The Interlakes karst region of Manitoba.

An aside – the beauty of Little Limestone Lake, Manitoba.

This is an example of limestone crystallite ‘bloom’ (a typically tropical phenomenon) occuring in a cool climate due to highly buffered spring water and summer heating in a shallow lake.

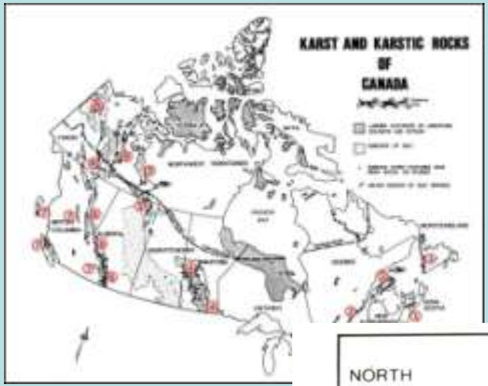


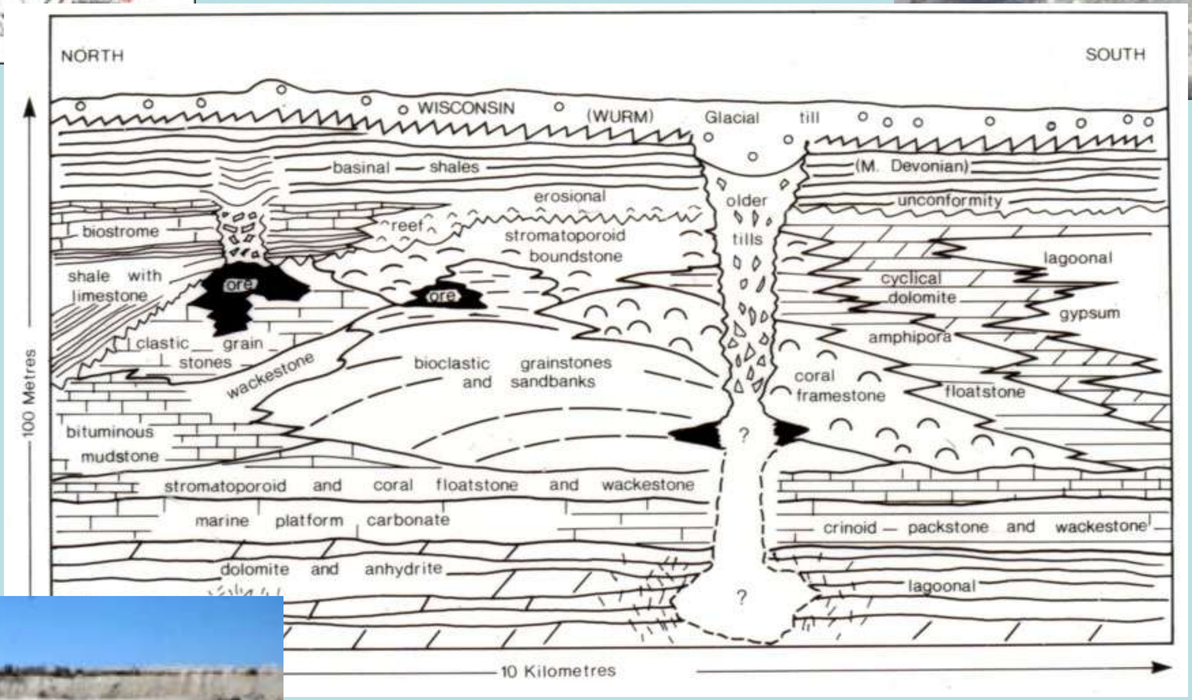
A model for the intense blue colour of Little Limestone Lake.

The lake rests on dolomite and is surrounded by dolomite-rich glacial tills which have high porosity and permeability. It is fed largely or entirely by springs from the till. The spring water is much enriched in Ca^{2+}, Mg^{2+} and HCO_3^- ions which have been dissolved from dolomite fragments in the till; their concentration becomes very high in summer when CO_2 builds up in the soil to levels 10 – 100 times greater than in the open air due to bacterial activity. The CO_2 combines with seeping waters to form carbonic acid (H_2CO_3) to dissolve the dolomite.

The lake is very shallow and so warms well in summer. Warming of the enriched spring waters causes expulsion of CO_2 from some HCO_3^- ions, causing them to combine with Ca^{2+} to precipitate $CaCO_3$ either in the crystal form (“habit”) of aragonite or in the more common habit of calcite. I suspect that at Little Limestone Lake most of it is aragonite, which usually is limited to tropical seas because of their combination of warmth and high Mg^{2+} content. The solid $CaCO_3$ particles then settle out to form marl on the lake bottom. It is their scattering of light as they settle that creates the blue colouring.

Little Limestone Lake is very much the finest example of a marl lake that I have seen anywhere in either hemisphere.





Glacial impacts at the Pine Point paleokarst zinc/lead deposits, Northwest Territories.
The ores fill sinkholes and caves in dolomitised Devonian reefal strata. Glacial flexure and injection rejuvenated some of the sinkholes and extended the base of karstification to lower beds.

Sub-glacial initiation of karst - where it is too cold for normal groundwater circulation in interglacial or modern post-glacial conditions

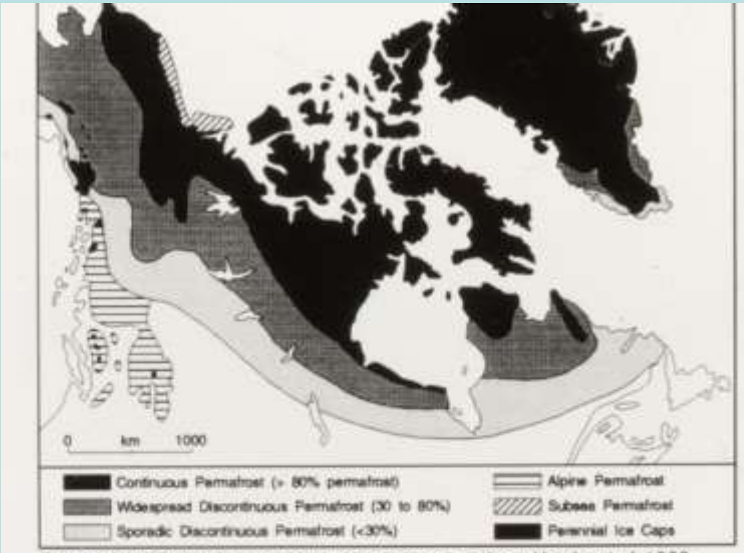
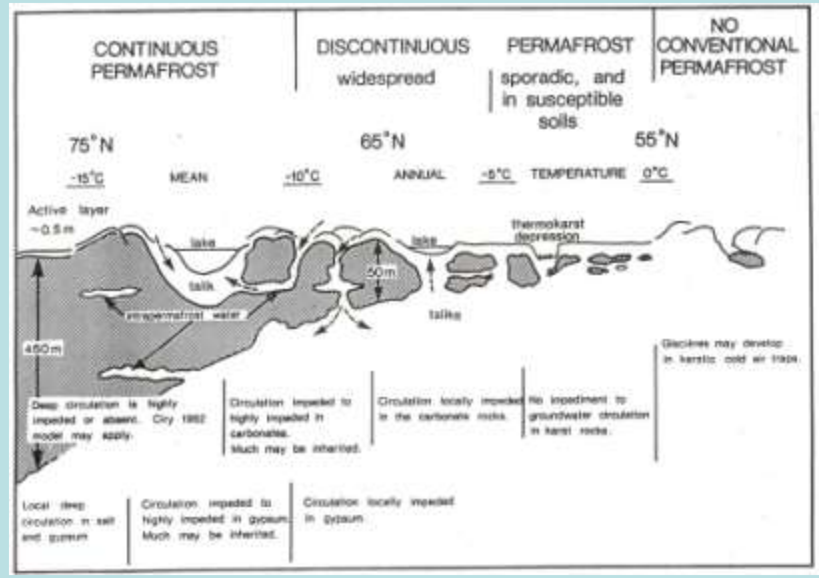
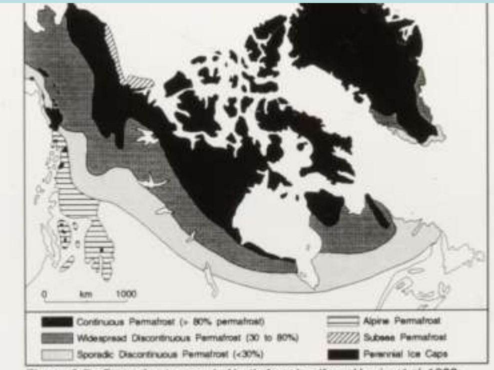


Figure 2.7: Permafrost zones in North America (from Harris *et al*, 1988; after Harris, 1986; Heginbottom, 1984; Johnston, 1981).



Karst under felsenmeer at the rims of valleys only.



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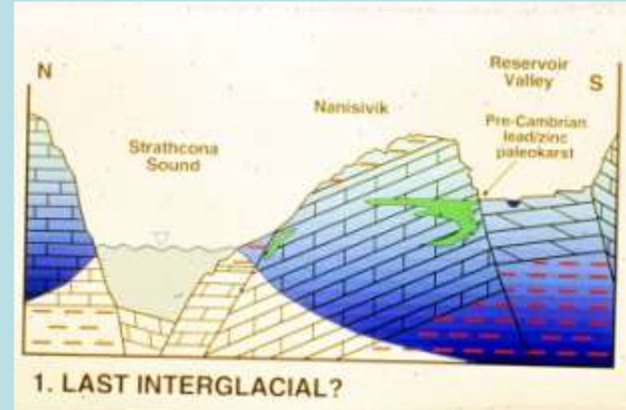
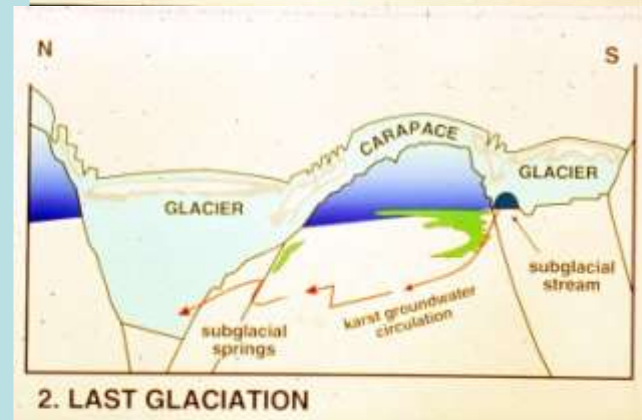
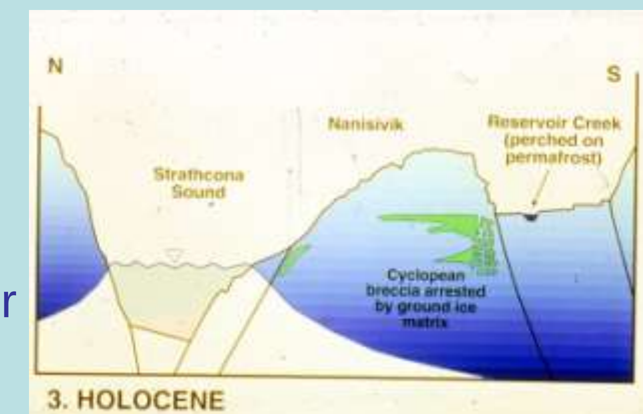






At Nanisivik zinc-lead mine, Baffin Island, the permafrost temperature is -13 C today. Under glacier ice cover during the last glaciation geothermal heat thawed the permafrost, allowing groundwater flow that induced a mega-breccia collapse along the south side of the ore body.

Conclusions

The effects of glacial action on karst aquifers and landforms are chiefly destructive or inhibitive but, in particular conditions, they may create karst features very rapidly, including some of the largest collapse structures known on the planet.

Some examples to show the extent of post-glacial karst landform development in Canada

The sink of Salmon River, Anticosti Island, Quebec

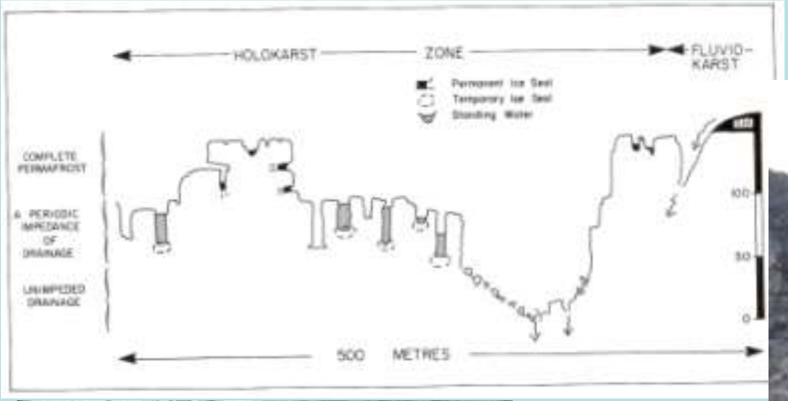
Pavement on limestone, pure and impure dolomite in Ontario.


Collapse dolines in dolomite over gypsum, northern Alberta and Mackenzie Valley

Typical kotlic in the Rockies


Dense karst in limestones on the very wet west coast

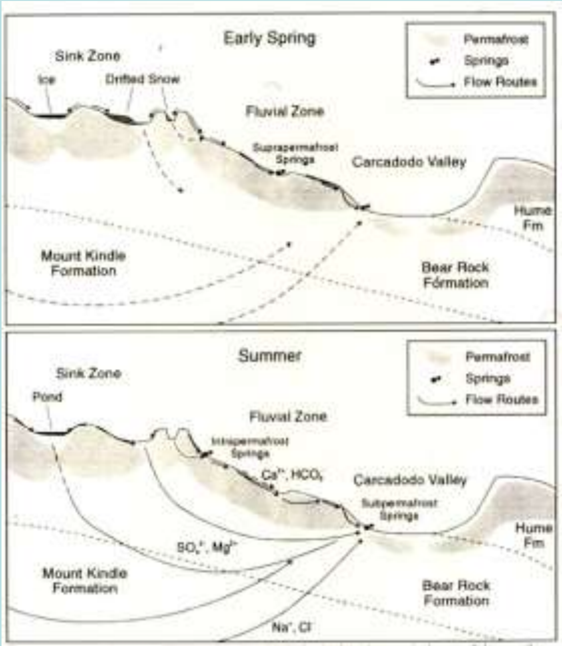
Periglacial - rugged










Early Spring
Permafrost
Springs
Flow Routes
Sink Zone
Ice
Drifted Snow
Fluvial Zone
Suprapermafrost Springs
Carcadodo Valley
Hume Fm
Mount Kindle Formation
Bear Rock Formation
Summer
Permafrost
Springs
Flow Routes
Sink Zone
Pond
Fluvial Zone
Intrapermafrost Springs
Ca^{2+}, HCO_3^-
Carcadodo Valley
Subpermafrost Springs
Hume Fm
SO_4^{2-}, Mg^{2+}
Mount Kindle Formation
Bear Rock Formation
Na^+, Cl^-