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Karst Geomorphology

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PRINCIPAL FEATURES OF EVAPORITE KARST IN CANADA

ABSTRACT: FORD D.C., *Principal Features of Evaporite Karst in Canada*. (IT ISSN 0391-9838, 1998).

Outcrops of sulfate and mixed sulfate-carbonate rocks are common everywhere in Canada outside of the Shield province. Interstratal salt deposits are abundant in the interior lowlands. Types of karst that occur are determined chiefly by relations between (i) formation thickness and purity, (ii) regional topography and hydraulic gradient, (iii) effects of receding Wisconsinan and earlier glaciers, and (iv) extent of modern permafrost.

Exposures of bare karst on thick, pure sulfate formations are comparatively rare. Two principal landform types found on them are: (1) high-density polygonal karst (micro-sinkhole densities of thousands per km^2), where hydraulic gradients are high and tills are thin; (2) hills and ridges of blocks uplifted and fractured by hydration (anhydrite) tectonics at paleo-icefront positions where hydraulic gradients are low. Deeply till-mantled karst dominated by collapse and suffosion sinkholes in the mantling detritus is well developed in southwestern Newfoundland and in central and northern Nova Scotia. Covered karst is abundant on sulfates conformably overlain by carbonate or clastic strata; collapse sinkholes are the principal landform. Very large breccia pipes (up to 25 x 15 km) are associated with deep subrosion of salt during glacier recessions. Syngenetic breccia karst is a fourth, distinct category created in some formations of thin, interbedded dolostones and sulfates. Where these are exposed to high hydraulic gradients, deep calcite-cemented breccias were formed in a first generation, upon which sinkhole and pinnacle karsts and dissolution drape topographies were able to develop rapidly in late-glacial and post-glacial conditions.

KEY WORDS: Karst, Morphology, Evaporites, Canada.

INTRODUCTION

There are approximately 80,000 km^2 of evaporite outcrops in Canada (Quinlan & Ford, 1973). These rocks are found in all the major geological provinces (fig. 1) although, not surprisingly, they are rare in the Precambrian Shield. In terms of karst development upon them, they may be divided into two distinct groups. (1) Pure evaporite formations sufficiently thick that they may host substantial karst groundwater circulation and landform genesis wholly within themselves; usually this requires minimum thicknesses of ten metres or more. (2) Mixed units where the evaporite beds are intimately interspersed with other strata, principally dolostones or red beds; preferential dissolution removes the evaporites locally or regionally, leaving a topography that is exposed largely or entirely in the other rocks. Both categories are important in Canada.

In the Maritime Provinces and Newfoundland, karst is well developed in gypsum and anhydrite belonging to the Mississippian Windsor Group', which also includes thick red bed sequences and some minor salt (Baird, 1959; Sweet, 1978; Roland, 1982; Martinez & Boehner, 1997). In southwest Newfoundland (fig. 1, area 1), northern Nova Scotia (Cape Breton Island, area 2), New Brunswick and the Magdalen Islands, most evaporites have been highly deformed by Appalachian tectonics and crop out as narrow, linear ridges or as less regular patches that are highly variable in thickness. Salt is present at depth locally but does not appear to be karstified to a significant extent. Around Minas Basin (Bay of Fundy) and Windsor, Nova Scotia (area 3), the deformation is less intense and there are extensive areas of gypsum beds that remain nearly horizontal. Core stones of unaltered anhydrite are common in some freshly exposed outcrops in all these areas, but drilling has revealed hydration to gypsum at depths of 200 m or more.

The greatest evaporite deposits of Canada are found in the sedimentary platforms surrounding the Canadian Shield. The rocks are little deformed. Age of the evaporites is from Ordovician to Jurassic but most belong to the Silurian or Devonian. In the Hudson Bay Lowlands aggregate thicknesses of the carbonate and sulfate sequences range

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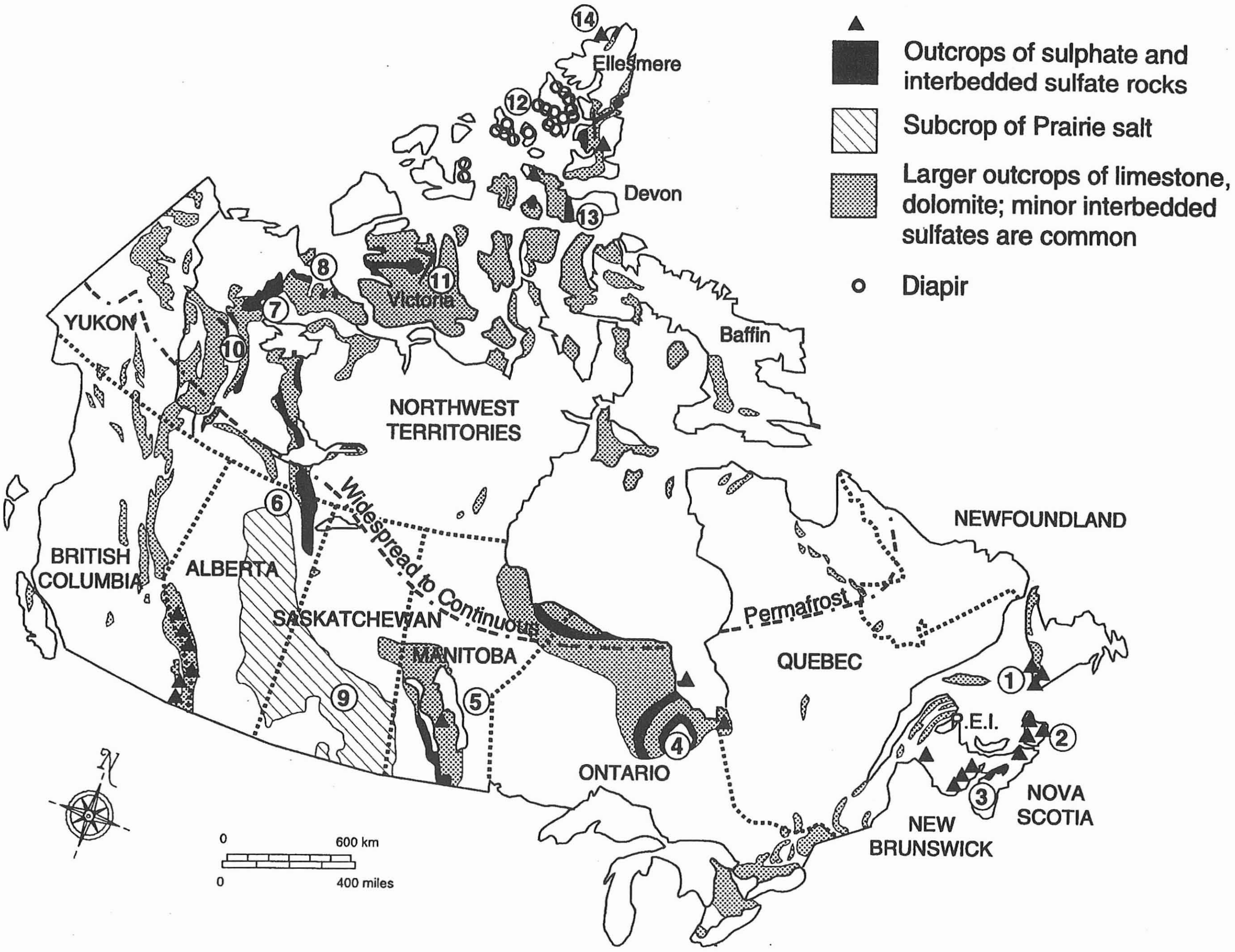

FIG. 1 - Principal outcrops of sulfate rocks and subcrops of salt in Canada. Numbers locate areas mentioned in the text.

from 450-800 m (Stockwell & *alii*, 1970) but the topographic relief is generally very low and bedrocks are buried by thick marine clays of the finiglacial «Tyrrell Sea», inhibiting effective groundwater circulation. Gypsum karst is reported in some local outcrops in the southeast of the region (fig. 1 - area 4; Sanford, 1968). In the Great Lakes - St. Lawrence Lowlands, evaporites are largely limited to southwestern Ontario. There is a pronounced salt-dissolution slope or zero sub-edge (German-salzhange) in the strata beneath Lake Erie. Gypsum is mined near Hamilton and salt at Windsor (Ontario) but it appears that the significant modern karstification is occurring further west, in the Michigan Peninsula (see Black, 1997).

«The lithological trinity of dolostone, limestone and sulfates» (Friedman, 1997) dominates the Paleozoic sequence that extends along the west side of the Shield from the 49th Parallel to the Arctic Ocean. It includes some thick formations of pure sulfate which, however, tend to be recessive and thus of very low relief, deeply buried by glacial and postglacial sediments and karstically inert. Karst is more prominent and widespread where the sulfates are protected by relatively thin dolostone caprocks, as in much of Wood Buffalo National Park, around the West Arm of Great Bear Lake and in the Horton Plain further north (fig. 1, Areas 6, 7 and 8 respectively).

Farther to the west in Saskatchewan and Alberta are salts of the Elk Point Group (Upper Devonian). Their extent is more than 500,000 km^2. The principal deposit, the Prairie Formation, is composed of fine- to coarse-grained halite plus upper sylvite and carnallite and some anhydrite interbeds; the formation is 0-210 m thick. There are two additional salts beneath it in parts of Alberta that locally increase aggregate thicknesses to more than 400 m (Belyea, 1959). The top of the salt is now at depths of 200 to 2500 m; the cover rocks are chiefly siliclastic strata of Mesozoic to Tertiary age. Anderson and Hinds (1997) discuss examples of karstification in Alberta elsewhere in this Symposium.

In the Western Cordillera sulfate rocks are present chiefly as either thin formations or scattered interbeds in the great carbonate sequences of the Rocky Mountains and Mackenzie Mountains. There are only a few karst features reported in the south (e.g. at Skookumchuck, B.C.; Wigley & *alii*, 1973). North of 60° the distinctive Bear Rock Formation (Devonian) hosts some spectacular breccia karsts in the Franklin Mountains and Carcajou Range (fig. 1, area 10) that are given separate status as phenomena in this review (see below). There is also an extensive sulfate, salt and red-bed formation, the Saline River (Cambrian), that may be contributing to the genesis of some recent and modern collapse sinkholes.

Karst groundwater circulation and landform genesis become progressively inhibited northwards in the arctic islands, where there is continuous permafrost today. From air-photo analysis it is possible that there is some local karst development at 72°N in Precambrian sulfates exposed in the Shaler Mountains of Victoria Island and at 78°N in salt diapirs on Axel Heiberg Island (fig. 1, areas 11 and 12, respectively). The author has suggested that karst groundwater circulation in dolostones of northern Baffin Island (74°N) was renewed when the ground thawed beneath a protective cover of flowing glacier ice during the last glaciation (Ford, 1987). This effect may also explain the existence of a group of apparently inactive dolines in gypsum on Devon Island (75°N; area 13) and an arrested dissolution breccia at 82°N on Ellesmere Island (area 14).

All of the significant evaporite outcrops were glacierised during the last (Wisconsinan) glaciation, with the probable exception of some small areas of gypsum exposure in the Magdalen Islands, Gulf of St. Lawrence. Glacier scour can be expected to modify or remove many pre-existing karst features on these comparatively soft rocks, while the large quantities of till, outwash and lacustrine sediments released during the glacial recession may have mantled or buried those that survived. The fact of recent glaciation must always be considered when interpreting the nature and distribution of evaporite karst in Canada but, as is shown below, it must not be over-emphasized. Much of the karst is very similar to that on evaporites in extraglacial regions worldwide.

CATEGORIES OF EVAPORITE KARST LANDFORMS IN CANADA

With present knowledge it is helpful to assign the evaporite karst of Canada to four distinct genetic categories although, in the field, there is often admixture of two or more of them. The categories are bare and thinly mantled, deeply mantled, covered, and syngenetic breccia karst. The remainder of this review summarises each in turn.

Bare Evaporite Karst

«Bare» describes both truly bare rocks and those that are so thinly masked by glacial till or other debris that they are not protected against dissolution by descending meteoric waters to any significant extent. At some sites in Nova Scotia it can be shown that two metres of till containing clasts of local gypsum has sufficed to shield the underlying sulfate bedrock from any postglacial dissolution (Ford, 1987). Where there is no sulfate in the detritus, even thicker mantles may offer no protection.

There are only very small areas of pure sulfate formations exposed in this manner in Canada and effectively no exposures of pure salt. Characteristic landforms developed such areas include small gypsum «tents» (hydration/recrystallisation pop-ups), small sinkholes and circular shafts, linear troughs (grikes or kluftkarren), short caves and natural bridges. Truly bare surfaces become indented with solution pits and runnels (rillenkarren, rinnenkarren) within a few years of exposure. The spatial density of such features can be very high but they rarely extend over areas greater than one or two square kilometres at most or have a local relief greater than ten metres. «Gypsum Mountain» (fig. 1, area 4) is a good example in Ontario, being a domal structure some 500 m in diameter that rises 8 m above a surrounding muskeg (Sanford & *alii*, 1968). Gypsumville, Manitoba (area 5) is similar though larger (Voitivici & McRitchie, 1989). Tunago Ridge (area 7) is a greater feature, a linear ridge of jumbled mega-blocks of gypsum that extends for 20 km and has local relief up to 60 m; van Everdingen (1981) suggests that it may be a product of hydration along a stationary glacier icefront.

Schlottenkarren

The most distinctive bare karst topography consists of densely packed, funnel-shaped sinkholes draining into vertical cylindrical shafts. It is developed best where groundwater hydraulic gradients are steepest, i.e. along the rims of cliffs. It rarely extends more than a few hundred metres back of them. Dissolution of the funnels downwards may leave residual pinnacles upstanding between them, creating a rugged pinnacle-and-shaft mini-landscape where the individual features are only a pace or two apart. fig. 2 presents a schematic illustration of the form as it appears around Windsor, Nova Scotia.

This topography has long been appreciated in the Maritime Provinces. In a report dated 1868, Dawson adopted a local term «plaster topography» to describe it (although he extended this to include larger, common solutional, collapse or suffosion sinkhole clusters in gypsum as well). Internationally it is better known from discussion of examples in Germany and Austria by Penck (1924), Seedorf (1955), Priesnitz (1969) and others. The term «schlotten» is widely applied to it (Ford & Williams, 1989, p. 391): Stenson (1990) points out that Penck used schlotten' for the underlying cavities, however, and suggests that «schlottenkarren» is more appropriate for the assemblage.

The best Canadian examples known to the author are above river cliffs at Windsor and Cape North, Nova Scotia, and at Romaine's Brook, Newfoundland. Local relief of the pinnacle-shaft combination is as much as 10-20 m at these sites. There are smaller displays described elsewhere in Nova Scotia (Moseley, 1996), New Brunswick (Schroe-

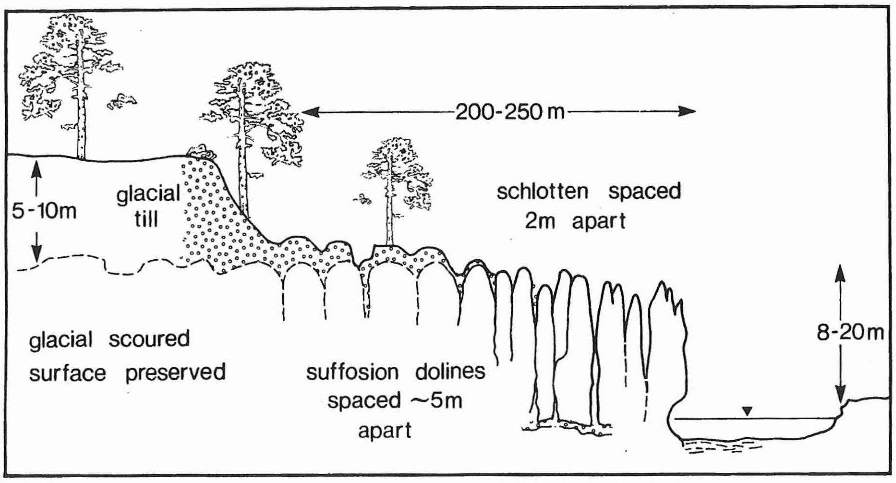

FIG. 2 - Model for the development of schlotten («plaster») topography in massive gypsum near Windsor, Nova Scotia.

der & Arsenault, 1978), Manitoba (Bannatyne, 1959) and Wood Buffalo National Park (Drake, 1970).

Stenson (1990) has undertaken a thorough morphometric analysis of the principal Nova Scotian occurrences. At 19 of 23 sample sites he found mean sinkhole rim diameters to range between 0.5 and 1.5 m, with little variance: means were larger (1.8-3.5 m) at the other sites. Mean nearest neighbour distances between sinkhole centers at the sites ranged 1.0 to 3.5 m. The mean nearest neighbour distribution statistic, R, for the patterns of the centers fell between 1.35 and 2.05 for the 19 sites. Where R = 1.0, the distribution is ideally random; where R = 2.15, it is precisely uniform (Clark and Evans 1954). It appears that these mini-sinkholes form initially at random (or controlled by particular structural or lithological factors, etc.), but that later individuals develop between the early ones. The process is space-competitive, driving the distribution to a nearly uniform one where the initial ground surface is not too rugged or steeply inclined.

Although these particular schlotten developed upon surfaces previously karstified and then glaciated (see next section), they are not specific to either inherited karst or to glaciated regions. German examples in gypsum include unglaciated regions in the Harz Mountains and there are others south of glacial limits in the Urals (Gorbunova 1965). The author has seen ideal examples developed on salt mine spoil heaps near Perm (Russia) that were no more than ten years old; the density appeared to be somewhat higher than on gypsum. The essential requirements are the exposure of rather pure evaporite bedrock, high hydraulic gradient and sufficient precipitation.

Deeply Till-Mantled Karst

When there is a deep cover of glacial or associated postglacial deposits sulfate strata may be shielded, partially or completely, from dissolutional attack by descending meteoric waters. This is the case for most of the «outcrop» of sulfates mapped in the Hudson Bay Lowlands, Manitoba and the northwest plains in fig. 1. Bedrock units are buried by 10-60 m of till, etc., topographic relief and hydraulic gradients are very low, and regional watertables are generally in the overburden. This is a very constricting environment for modern karstification, which tends to be limited to the few places where groundwater can attack the bedrock laterally from entrenched river gorges.

Karst areas of southwestern Newfoundland, Nova Scotia and New Brunswick are the prime examples of deeply mantled evaporite karst in Canada. It is difficult to place them within any simple genetic model. Form, scale and distribution of the landforms are highly irregular and unpredictable. This is because: (i) as noted, lithology and geologic structure are most often complex, the evaporites and clastic sequences being much faulted, tightly folded, displaying vertical bedding, etc.; (ii) before the last (Wisconsinan) glaciation, rugged topography had been carved into this complex by rivers, karst processes and earlier glaciers; (iii) Wisconsinan ice scoured, infilled and then buried this topography. The modern surfaces are thus of glacial and glacio-marine deposition that are locally entrenched by post-glacial rivers. Bedrock is exposed only in a few river or sea cliffs and a handful of deep sinkholes. Paleo-schlotten surfaces, laid bare by removal of overburden in preparation for quarrying, suggest that no more than one or two metres of gypsum may have been removed by the Wisconsinan glacial scour, a surprisingly small amount for such soft rocks. Most natural cliffs and quarry faces, however, display one or more examples of large dissolutional sinkholes in the gypsum that were infilled, then buried completely by glacial detritus and rendered inert (i.e. converted into paleokarst). Cliff recession now exposes them in cross-section. Some contain organic remains at the base of the fillings that are attributed to Wisconsinan glacial interstades or to the last (Sangamon) interglacial (Moseley 1996): in certain instances they could be much older.

Modern karst is represented primarily by collapse and suffosion (ravelling) sinkholes developed in the overburden. In very few instances is gypsum exposed beneath it. Sinkhole diameters range from less than five metres to greater than 500 m, depths from a few metres to 60 m in exceptional cases. At the regional scale their gross distribution reflects that of the gypsum; although much of the pre-Wisconsinan karst may remain buried and inert, it appears that at least a few postglacial depressions have been able to form on all of the «outcrops.» At the local scale, many sinkholes are aligned, presumably over buried gypsum ridges of structural or erosional origin (Baird, 1959; Schroeder & Arsenault, 1978). Others are distributed at random. Many of the largest occur where postglacial creeks entrenching into the till encountered buried ridges and could attack them laterally; «Loch Leven» in Newfoundland (Baird, 1959) is a pond sinkhole nearly 800 m in diameter with a river channel diverted into it and out again. The larger, deeper sinkholes often contain ponds. In perhaps a majority of instances these are at a regional watertable and, where gypsum is exposed at and below the waterline, they may be expanding actively (cf. Martinez & Boehner, 1997). In other cases, the topographic depression created by collapse or suffosion was contained entirely in the overburden; its floor has become sealed with clay and organics, perching a pond that may overflow seasonally.

The cave systems that drain the sinkholes are mostly inaccessible due to their small size, to permanent flooding, to clogging by bedrock breakdown or till slumping in. Moseley (1996) summarises those that are known in Nova Scotia. River passages are most common; their morphology is dominated by ceiling breakdown but earlier corrosion notches and bevels (German-laugdecken) that formed at ponding surfaces are often preserved. Hayes Cave, 400 m long, is the longest explored example. There are also a few small dissolutional mazes formed along joints.

Fig. 3 displays the Woodville area, Newfoundland, as an instance of this deeply mantled, complex karst. The surface is a till plain descending gently to coastal, wave-cut cliffs. All sinkholes are expressed only in the till. Buried ribs of gypsum and red shale with near-vertical dip are exposed in the sea cliffs, where they are separated by till-filled ravines that extend below modern sea level. There are sulfate-rich springs at the base of the cliff and up to 100 m offshore. Sinkhole density is >100/km^2. Sinkhole diameter ranges through three orders of magnitude. Some sinkholes are aligned along buried gypsum ribs or the entrenched creeks, others are randomly distributed. Three large ponds in the northeast sector are interpreted as early sinkholes whose form has been much modified by slumping and clogging. New collapses are still occurring. In 1965, a sinkhole 45 m in diameter and 15 m deep formed within a few hours.

Covered Evaporite Karst

Dissolution landforms created beneath a cover of later, consolidated strata are probably the most common expression of evaporite karst worldwide (Quinlan, 1978). The principal surface features are collapse sinkholes (with the exposed depression being largely or entirely in the cover rocks), sinking streams, springs and springhead gorges. Most of the world's very extensive gypsum caves are also protected by some cover (e.g. Klimchouk, 1992). A separate, distinctive class of features are breccia pipes or geological organs, created by stoping upwards from very deeply

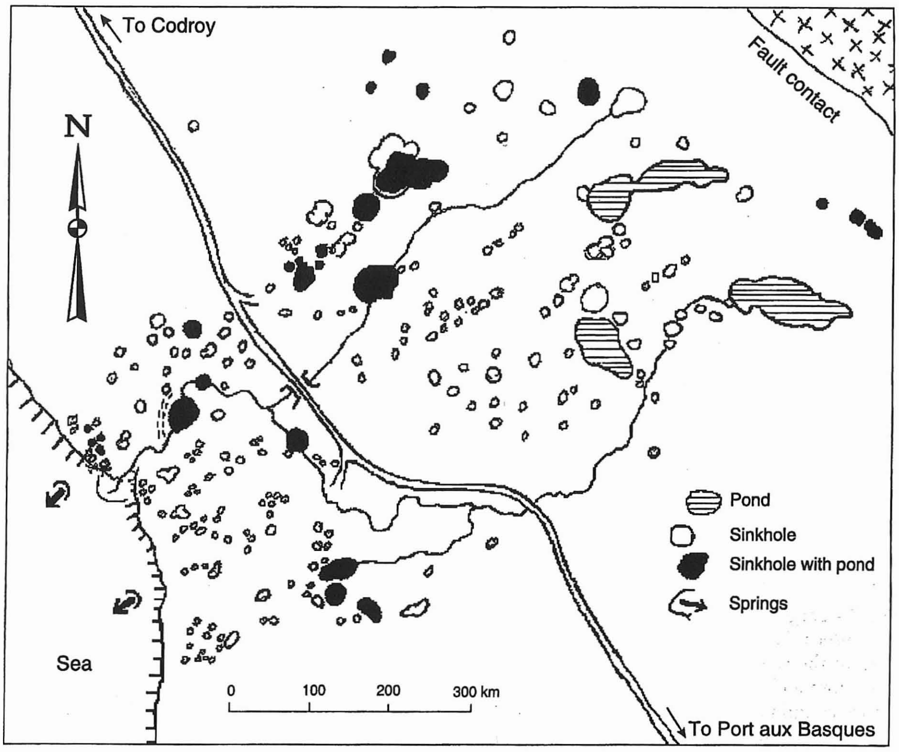

FIG. 3 - Map of an example of deeply till-mantled karst near Woodville, Newfoundland (adapted from Sweet 1978).

covered evaporites, usually salt: they may have no surface topographic expression today but are not necessarily inert.

In Canada, the principal areas of covered karst with modern expression are in sulfates along the NW edge of the Shield, including Wood Buffalo National Park (Ozoray, 1977), the Franklin Mountains and Great Bear Lake (area 7; Yorath & *alii*, 1968). Cover strata are chiefly dolostones or dolomitic shales a few metres to tens of metres thick. The strata are nearly horizontal in attitude. Most karst occurs where hydraulic gradients are relatively steep, i.e. along the flanks of entrenched river valleys or receding escarpments in the cover rocks. The sinkholes are mostly postglacial in age; Tsui & Cruden (1984) give examples of rapid modern evolution in the Wood Buffalo region. Van Everdingen (1981) has studied the shallow plateaus and outlying ranges of the Franklin Mountains around the west arm of Great Bear Lake, mapping more than 1400 large sinkholes (e.g. fig. 4), 27 greater, polje-like depressions that are seasonally inundated, and at least 63 substantial karst springs that form «icings» in the winter. Whereas the majority of the sinkholes are post-glacial, many of the poljes may be older, till-clogged karstic groundwater systems that are now being rejuvenated.

In the Prairie Provinces, the Elk Point salt is covered by 200-2500 m of later consolidated rocks, chiefly clastics. Exploration for potash and oil have revealed many classic features of salt subrosion, including an eastern sub-edge (salzhange) that has receded an average of 200 km westward since the Devonian, a major re-entrant in the southwest (the Regina-Hummingbird Trough), and more than 60 large breccia pipes. Many of these features appear to have been inert throughout the Quaternary record that is preserved, i.e. there is no recognised deformation in Quaternary sediments overlying the older clastic cover strata that have been brecciated. Subrosion of the Trough may be related to fluid flow resulting from Mesozoic tectonic displacements in the craton below (de Mille & *alii*, 1964). Gendzwill (1978) suggests that many breccia pipes formed where Phanerozoic basinal fluids were able to circulate through individual pinnacle reefs buried by the salt, thus removing the latter from below.

Certain subrosional troughs and breccia pipes can be firmly linked to effects of Quaternary regional glaciation, glacial recession and crustal isostatic rebound, although it is possible that their initiation was older. Anderson and Hinds (1997) present new examples from Alberta. In Saskatchewan, Christiansen (1967, 1971) has analysed two features in detail. Howe Lake is a depression where Wisconsinan tills display cylindrical faulting with a downthrow of 78 m. Collapse occurred immediately after the ice receded (Christiansen, 1971). The depression has been filling slowly with gyttja, local soilwash, airborne dust etc. throughout the Holocene and is now only 10 m deep although it is 300 m in diameter. The «Saskatoon Low» (fig. 5) is a much larger geological feature but it has no modern topographic expression. From the data and analysis of Christiansen (1967), in one or a series of early collapses Upper Cretaceous and older shales were downfaulted at least 190 m to create one large depression measuring 25x40 km, plus three lesser ones on its flanks. Christiansen considered that these collapses could have occurred during the Tertiary, but there was no exceptional hydrological mechanism to produce them then and no evidence to indicate that they are not Quaternary glacial in their age: I suspect that they are. The most recent collapse was contained largely within the principal older feature and occurred precisely at the close of the last glaciation. Tills of that age were downfaulted 70 m, then the new depression was infilled entirely with proglacial lake sediments. It has been stable in postglacial time. The collapse propagated from salt with its base resting on dolostone 1100 m below the modern prairie surface.

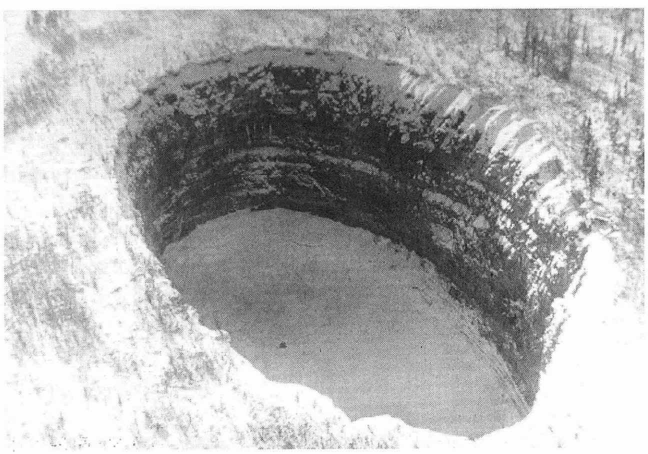

FIG. 4 - Large collapse sinkhole near Vermillion Creek, 34 km SE of Norman Wells, NWT. Approximate dimensions are 60 x 120 m and 40 m deep to the waterline. Collapse is believed to have propagated from the Fort Norman Formation (anhydrite and dolostone), through overlying limestones and into the Canol Formation (Late Devonian) which forms the exposed walls. (Photo by R.O. van Everdingen).

Syngenetic Breccia Karst

These landforms develop upon a remarkable geological formation in the central Mackenzie Valley region, NWT (fig. 1, area 10). In outcrop it is formally named the Bear Rock Formation, and where covered by later consolidated strata it is the Fort Norman Fm. (Meijer Drees, 1993). It is Late Silurian-Early Devonian in age and is more than 50,000 km^2 in extent.

In exploration cores the Fort Norman Formation is 250-350 m or more in thickness. It consists of a thin upper limestone (Landry Member), a central Brecciated Member and, in some cores, undisturbed lower sequences of interbedded dolostones and anhydrites that are recognised as sabkha facies. It is conformably overlain by 90-150 m of limestones and calcareous shales (Hume Formation-Eifelian). Typical covered karst can develop through the Hume and higher formations (fig. 4) as a consequence of interstratal dissolution of the Fort Norman, where meteoric groundwater circulation and sulfate dissolution have been recorded at core depths as great as 900 m.

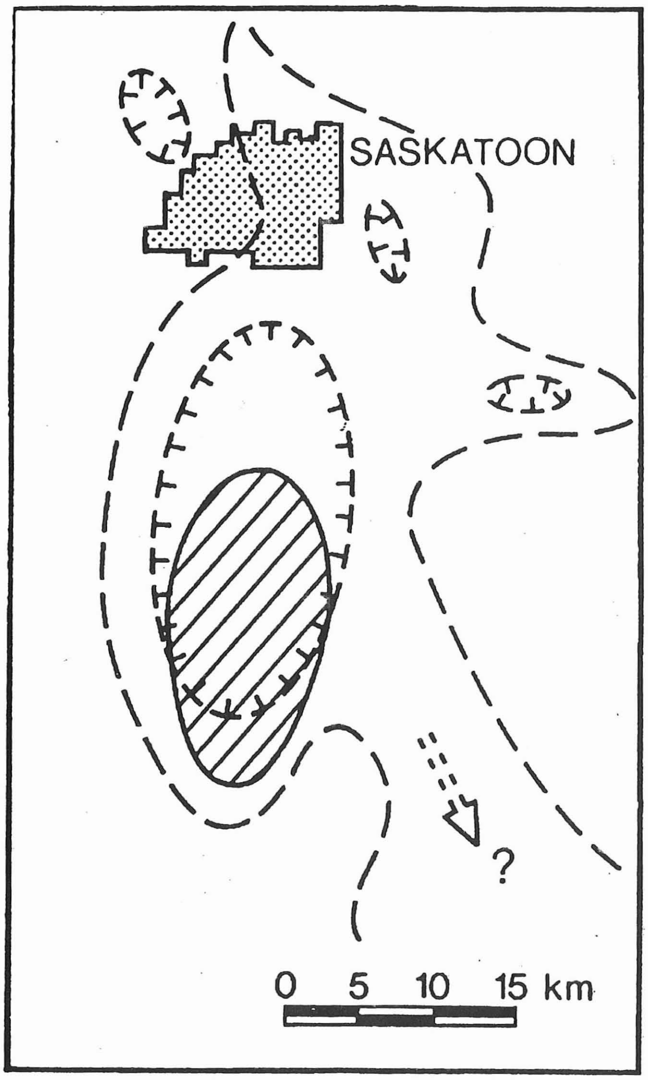

FIG. 5 - The «Saskatoon Low» (adapted from Christiansen 1971, with permission). Broken hachures mark location of four closed depressions in bedrock that are now concealed by mantles of glacial and glaciolacustrine debris. The cross-hatched feature is a younger collapse inside the largest of these depressions: collapse of 70 m occurred at the close of the last Wisconsinan) glaciation.

The Bear Rock Formation is a solution breccia up to 250 m thick. If present, the Landry Member is a brecciated limestone no more than 20 m thick. The main breccia is most striking, a chaotic, vuggy mixture of limestone, dolomite, and dedolomite clasts variably cemented by later calcites, with small residual clasts and secondary encrustations of gypsum. Pack breccias (Stanton, 1966; James & Choquette, 1988) displaying rubble fabric (predominant), crackle or mosaic fabric, are common and cliff-forming. Float breccias are rarer and tend to be recessive. Meijer Drees (1989) classifies the Formation as a late diagenetic' solution breccia created by meteoric waters. Hamilton (1995) shows that calcite, dolomite and sulfate dissolution, plus dedolomitisation with calcite precipitation, are proceeding in it today. They are re-working older fabrics, creating new ones and forming a suite of surficial karstic depressions that range from a few metres to several km in scale: the complete assemblage may be categorized as a «syngenetic breccia karst».

Detailed studies have focussed on Bear Rock and the Mackay Range, which are outlying highlands on the east and west banks respectively of the Mackenzie River, and terrain between Carcajou Canyon and Dodo Canyon in the Mackenzie Mountains (Hamilton, 1995). These sites were covered by the Laurentide Ice Sheet (Wisconsinan) but were close to its western, sluggish margin. They are at the boundary between Widespread and Continuous permafrost in the ground today and display some year-round groundwater circulation via taliks. Thaw/freeze and solifluction processes compete with dissolution to mold the topography.

The principal karst landforms are varieties of sinkholes, blind valleys, solution-subsidence troughs and fault-bounded depressions (fig. 6). Sinkholes range from single collapse features a few metres in diameter to merged or compound dolines (Slovene-uvalas) up to 1.5 km^2 and 100 m deep. Smaller individual sinkholes may retain seasonal meltwater ponds, and there are permanent lakes draining to marginal ponors in some of the larger uvalas. Blind valleys have developed where modern surface streams flow for several km into the karst from adjoining rocks. There are many relict, wholly dry valleys that may have been created by glacial meltwaters. Subsidence troughs have developed at the surface along contacts between the Bear Rock breccias and underlying, massive dolostones that are gently dipping. In the center of the Mackay Range and at Bear Rock itself are solution depressions formed where the

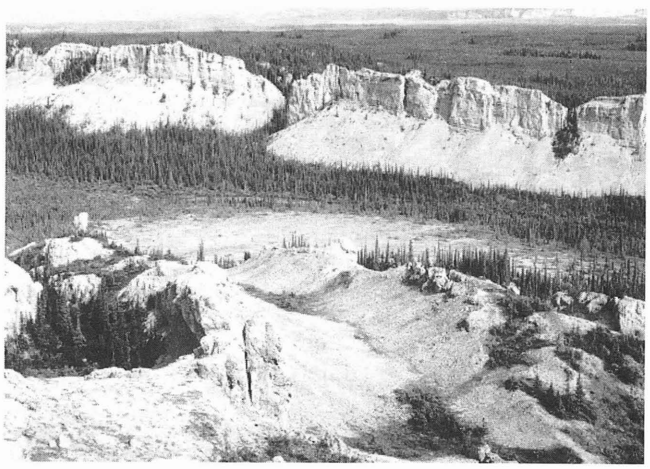

FIG. 6 - Karst in the Bear Rock Formation near Dodo Canyon, NWT. In the left foreground is a collapse sinkhole 50 m in diameter. Slabs of the resistant Landry Member are rotated vertically into it. In the right foreground, a dry valley with Landry capping slabs draped at many different angles. In the centre, sub-permafrost springs feed a creek in a glacial spillway; the creek sinks in Bear Rock strata just out of frame to right. Cliffs in the background are in the overlying Hume Formation (limestone), which displays many covered karst sinkholes. (Photo by J.P. Hamilton, with permission).

breccias are the hanging-wall strata on steeply inclined fault planes. The Mackay example is 3.2 km long, 1.0 km wide and 160 m deep.

Where patches of the Landry Member survive above the main breccias, they are often broken into large, separate slabs that tilt into adjoining depressions in sharply differing directions, creating a very distinctive topography of dissolution draping. Some slabs are rotated through 80-90°, as in fig. 6. Ridges (inter-sinkhole divides) that are wholly within the main breccias often display stronger cementation, represented by pinnacles as much as 30 m high (fig. 7). The only accessible caves are formed by a combination of dissolution and thaw/freeze processes where supra-permafrost groundwaters seep from cliffs. The many sinking streams pass through the permafrost via taliks and emerge as sub-permafrost springs at stratigraphic contacts or topographic low points.

Karst landform assemblages on the Bear Rock Formation are like no other in Canada, and the author has not seen or read of very similar topographies elsewhere. Their distinctiveness is attributed to repeated evaporite dissolution and brecciation, with dedolomitisation and local case hardening, during the Tertiary and Quaternary, in mountainous terrains subject to episodes of glaciation, permafrost formation and decay, and to vigorous periglacial action.

FIG. 7 - A 10 m high pinnacle in breccia of the Bear Rock Formation at Bear Rock, near Norman Wells, N.W.T. (Photo by the author).

CONCLUSIONS

This review is a first attempt to summarise what is known and understood concerning modern karst landforms occurring on evaporite rocks throughout Canada. The karst is shown to be very varied in its form and scale, and to be widespread geographically. Covered karst is the most common style; in most areas it, and the small outcrops of bare schlotten karst described above, are essentially the same as those that develop in unglaciated regions. Certain very large features above the Prairie salt may be products of deglaciation, however. The deeply till-mantled karsts of eastern Canada appear to be a product of the interplay of glacial, karstic and fluvial processes. They differ from evaporite karsts of unglaciated areas primarily in the close and unpredictable juxtaposition of their active, postglacial karst features with those that are older, buried and inert. The syngenetic breccia karst landforms on the Bear Rock Formation in the Northwest Territories display certain characteristics that are most unusual. These have been created primarily by the placement of thick dolostone-anhydrite interbedded sequences in a mountain tectonic setting that has permitted deep and vigorous circulation of meteoric groundwaters; however, glacial scour, melt and isostatic rebound, the growth and destruction of permafrost, and postglacial thaw-freeze processes have all added effects that have created distinctive polygenetic landscapes that are possibly unique.

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