Mapping Known and Potential Karst Areas in the Northwest Territories, Canada

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Executive Summary

The Goal of this Report is to Produce Maps of the Known and Potential Karst Landform Sites in the Northwest Territories (NWT)

Karst landforms are those created by the dissolution of comparatively soluble rocks and the routing of the water (from rain or snowmelt) underground via caves rather than at the surface in river channels. The principal karst rocks are salt (so soluble that it is scarcely seen at the surface in the NWT), gypsum and anhydrite (solubility around 2500 mg/l of water), and limestone and dolomite (solubility around 250 -350 mg/l). All of these rock types are common and widespread amongst the sedimentary strata in the NWT.

Surface karst landforms include:

a) *karren,* which are spreads of individually small solution pits, shafts, and runnels that, collectively, may cover many hectares (*limestone pavements*);
b) *sinkholes* of solutional, collapse, or other origin that can be tens to hundreds of metres in diameter and proportionally as deep. Sinkholes are considered the diagnostic karst landform worldwide;
c) larger topographically closed depressions that may flood or drain seasonally, *poljes* if flat-floored, otherwise *turloughs;*
d) extensive *dry valleys* and *gorges*, dry because their formative waters have been captured underground.

All water sinking underground via karst landforms of all sizes drain quickly in comparison with all other types of groundwater because they are able to flow through solutionally enlarged conduits, termed *caves* where they are of enterable size.

In principle, karst development in the NWT might be expected to be limited due to: (i) the impacts of repeated episodes of glaciation bulldozing sinkholes and blocking caves and (ii) the post-glacial growth of permafrost, which inhibits groundwater flow through the top few metres or tens of metres of the soil and rock. It is therefore surprising to find that karst landforms and groundwater flow are widespread in the NWT, and display great variety in both form and scale, the richest known anywhere in the arctic/sub-arctic regions of our planet.

Globally, karst is of great economic importance for water supplies with ~20% of the world's population partly to entirely dependent on it as a source. Limestone and dolomite are widely used for road and building stone and host economic minerals, and oil and gas. The karst-centred tourist industry is large, with income >$1 billion annually. There are more than 20 important karst areas amongst the UNESCO World Heritage natural properties, including Wood Buffalo and Nahanni National Parks in the NWT.

Report Methods and Their Limitations

All karst features detected were plotted onto the 38 1:250,000 scale topographic maps listed in Appendix A. This scale permits both (i) generalization to Territory-wide smaller map scales, and (ii) recognition of areas of special interest that may warrant mapping at the 1:50,000 scale. Some of the plotted data were derived from earlier work by the contractor, his research students, and published reports and maps of others; however, this covers only a small proportion of the total area of interest. Most of data derive from stereoscopic study, over four days in September 2008, of black-and-white 1:50,000 air photos at the National Air Photo Library (now Geomatics Canada), Ottawa. All flight lines were studied in areas judged of prime interest and only sample traverses were used where it was suspected that karst features would be very limited or absent entirely. All of the largest features detected were later checked against 1:50,000 topographic maps at McMaster University Library, Hamilton, for their accuracy of delineation.

The chief limitation of this work is that of the amount of time available for the air photo analysis. In addition, where the land is covered by boreal forest it is difficult to detect much limestone pavement and its associated alvar floral assemblages on the black-and-white air photographs, and small springs or sinkholes

Karst Regions of the Northwest Territories

On geological and physiographical grounds the karst development may be divided into seven differing regions, as follows:-

1. Southeastern Region (Topographic Sheets 85A –D)

Broadly from the Alberta border, west of Slave River, northwards to the shore of Great Slave Lake, and westwards to Kakisa Falls. It has upper and lower plains of limestone, dolomite and impure dolomites that are separated by a low, discontinuous escarpment. The dolomites are underlain by gypsum. The prominent karst landforms are collapse sinkholes 100 m or more in diameter created by gypsum dissolution undermining dolomite. More than 2000 large examples are found within the boundaries of Wood Buffalo National Park. There are also sinking rivers and many springs, including some salt springs that indicate long distances of underground flow for some of the water. The most concentrated and attractive karst is within the existing National Park but there are also important extensions northwards towards Pine Point. Further west some of the strata become less pure and soluble so that karst is largely reduced to spreads of pavement (e.g. around Alexandra Falls) that are difficult to detect on the air photos; some fine alvars have been reported there.

2. Horn Plateau and Gypsum Shorelines towards Yellowknife (Topographic Sheets 85E, 85L, 95I)

The Horn Plateau is an extensive upland of insoluble shale and sandstone rocks but streams spill from it onto lowlands underlain by limestone, dolomite, and gypsum. There is deep cover of glacial sands, clays and other materials over much of the lowland, creating muskeg and limiting the potential for any karst development. Two sinking streams and some small sinkholes were noted.

There are outcrops of gypsum along the north shore of Great Slave Lake and in its bays. There is potential for development of attractive coastal karst landforms but none could be observed in the 1:50,000 air photos and no reports were found.

3. Southern Mackenzie Mountains (Topographic Sheets 95B, 95F, 95G, 95J, 95K, 95M, 95N)

Broadly from the NWT/Alberta border at 60^{o} N latitude to the Redstone River. Karst landforms and groundwater systems are found in the Canyon Ranges, being very well developed in the Nahanni Limestone (~180 m in thickness) and in 1000 m of underlying dolomites. The prime development is within the existing Nahanni National Park Reserve and its expansion, which includes the full South Nahanni River basin and the Ram River basin. The surface karst landforms includes extensive spreads of limestone pavement, hundreds of solutional and collapse sinkholes, remarkable solutional corridors up to ten kilometres in length that often intersect each other to form areas of natural labyrinth, plus seasonal lakes and poljes, and four major dry canyons. The principal belt of karst drains to just two major springs, at the north and south ends respectively, which indicates a very high degree of integrated underground development of caves. The only accessible caves are now drained and relict, high in canyon or sinkhole walls. Examples are up to three kilometres in length and contain attractive calcite speleothems (stalactites and stalagmites) and some beautiful ice crystal deposits. The karst of the Nahanni and Ram basins is the most striking and accentuated limestone karst reported from any arctic or sub-arctic mountain area. It will be protected in its entirety within the boundary expansion of the National Park, which was announced in June 2009. .

To the northeast, the Iverson Range between the North Nahanni and Dahadinni River also display some interesting and significant karst at the surface that appears never to have been reported or studied. There are a few large sinkholes (including examples that are fresh-looking on the air photos), some Nahanni-type corridor karst, and one composite karst/alpine glacial landform, the “Horseshoe Lake Cirque” (unofficial name), that is unique amongst mountain karst landforms in this author’s experience.

4. McConnell Range (Topographic Sheets 95J, 95O, 96B, 96C)

Consists of the southern half of the Franklin Mountains, a sequence of fold and thrust mountain ranges east of the Mackenzie River. Its northern end is close to the community of Tulita and in the south it tapers out just to the north of Willowlake River near the community of Wrigley. The important karstic rocks include the Nahanni limestone, which is at the stratigraphic top. It is underlain by the series of dolomites with gypsum and salt that come to dominate all karst development further north, chiefly (i) the Franklin Mountain and Mount Kindle dolomites, thick to massively bedded and resistant dolomites, each ~400 m or more in thickness, overlain by (ii) the Bear Rock Formation which in outcrop is a breccia of dolomite fragments of all sizes that became broken up by the dissolving of interbedded gypsum and then re-cemented by calcite (the basic constituent of limestone) circulating through the debris. The Breccia varies from a few relict metres in thickness at some places to more than 200 m at others. It is one of the most remarkable karstic rocks that the author has seen, being intensely karstified and supporting many striking and unusual landforms.

The Franklin Mountains, including the McConnell Range, have been over-ridden repeatedly by the giant Laurentide Ice Sheet that buried all of Canada to the east during the Quaternary glaciations. As a result the mountain topography is everywhere strongly ice-moulded in form, in contrast to the Mackenzie Mountains to the west. Karst development has had to compete with glacial erosion and infilling processes.
At the north end of the McConnell Range, near the community of Tulita, small outlying uplands display some corridor karst, sinking streams, and irregular collapse over (probably) salt beneath the Franklin Mountain dolomite. In the much broader ranges to the south there are frequent occurrences of pavement and small sinkholes on the Nahanni limestone that are sometimes isolated, sometimes mingled with larger sinkholes, irregular depressions, and strings of rock pinnacles on the Breccia. Some quite large lakes in tributary valleys are captured underground. The combination of Nahanni limestone and the Breccia has permitted patches of dense and unusual karst topography to develop. Some of the big sinkholes (~100 m wide and perhaps as deep) appear to be very fresh, suggesting that there might be high rates of dissolutional activity in the Range today.

5. Northern Franklin Mountains, Low Plateaus, and Hydration Ridges between Great Bear Lake and the Mackenzie River (Topographic Sheets 96F, 96K, 96L, 96M, 96N, 106H and 106I)

This very large area includes two extensive but low plateaus, Mahony Dome and Tunago Dome, on either side of the Hare Indian River valley to the east and a series of mountain ranges comprising the northern Franklin Mountains to the west. North of Tunago Dome and the mountains, there is a remarkable series of abrupt but narrow ridges believed to be partly created by the hydration of anhydrite at shallow depths in the Bear Rock strata, beneath the front of the receding Laurentide Ice Sheet (Tunago Ridge, Lac Belot Ridge, Colville Hills, Lac Maunoir Ridge). They may be likened to fresh, elongated blisters imposed on the terrain by the glacier. Taken together, this assemblage of plateau karst, hydration ridges, and glacially overridden mountain karst must be considered to be one of the most significant, if not the most significant, karst known in permafrost on the planet.

Mahony Dome is a nearly flat plateau on Franklin Mountain dolomite, with many shallow sinkholes, sinking streams, and turloughs that broadly drain underground in a radial pattern towards the perimeter but with some preferential diversion of flow into the more sharply incised Hare Indian valley. Two particularly fine examples of turloughs and a beautiful sinking river were recommended for special notice and protection in Ford (2008). Tunago Dome is similar but displays some additional shallow corridor karst features. On its west side, Tunago Lake drains underground, at least partially, into Tunago Ridge. All of the hydration ridges display ruptured (burst blister) topography with sinkholes, lakes, and small rivers sinking in the fractures. Most remarkable is the underground capture of Lac Belot (>300 km^2 in area) into its ridge. The "Legend of Neyadalin" (a local Sahtu legend) has the underground river flowing rapidly >20 km to springs on a north bank tributary of the Hare Indian River. From a technical perspective, this is probable but has not been independently proven by dye tracing or other scientific method. The karst terrain on Bear Rock strata west of the Lac Belot Ridge and south to the Hare Indian valley is visually spectacular because of the exceptionally high density of sinkholes, turloughs, sinking lakes, and some pinnacle karst.

In the northern Franklin Mountains, the best karst development is seen along the Norman Range, which overlooks the community of Norman Wells. It displays fine examples of glaciokarst (ice-scoured) sinkholes, culminating in Bear Rock itself at the southern extremity, overlooking the community of Tulita. This important cultural site has major sinking lakes, pinnacle karst, and icings (perennial springs that freeze at their outlets in winter). On its flank to the north, Vermillion Creek Sinkhole is, simply, the finest example of fresh, symmetrical cylindrical, collapse morphology to be seen anywhere in Canada or the United States. Northwest of the community of Norman Wells, the Franklin Ranges become lower and narrower but each displays large sinkholes, sinking lakes, and rivers that, in any other region, would attract much attention.

6. Northern Extremities: the Horton and Anderson River plateaus, the Campbell Uplift, and the Parry Peninsula (Topographic Sheets 96O and 96P, 97A, 97B, 97C)

These are low, intensely ice-scoured plateaus between 67^o and 70^o N latitude, extending much deeper into the region of continuous permafrost. Bedrocks are the local equivalents of the Franklin Mountain and Mount Kindle dolomites. The principal karst development is seen on the flanks of the Horton River valley where, for a distance of 75 km through the taiga-tundra transition zone, the river has entrenched its course 50 to 140 meters below the general elevation of the plateau. This creates the hydraulic potential for tributary streams to pass underground to springs in the valley and it is evident that this has occurred. The air photos and the 1:50,000 topographic maps suggest that as many as 40 tributaries sink, at distances between 5 and 15 kilometers from the trunk valley. There appear to be some further sinkholes associated with a chain of esker ridges that have obstructed surface drainage to the south of the sinking stream belt. Such development, deep into the continuous permafrost zone and in the least soluble of the karst rocks, dolomite, is very surprising. It has not been studied and is worthy of investigation in the future.

Further west, Bear Rock strata are shown as outcropping in patches along the floor of the Anderson River valley. Geological survey reports mention sinkholes, filled with glacial debris, that are exposed in river cliffs in this region. Air photo analysis suggests only some minor development of small sinkholes out to four kilometres from the flanks of the valley. It is surprisingly limited when compared to the extent of the Horton River karst on purportedly less soluble rocks.

The Parry Peninsula, 69 to 70^o N latitude, represents the poleward limit of potential karst development in the Northwest Territories. It has a rugged surface of ice-scoured dolomites rising 50 to 80 m above sea level. There is some ice-modified corridor and sinkhole karst that appears to be inert (arrested by permafrost) today; this will be a test site to monitor the effects of global warming on permafrost degradation and re-establishment of karst groundwater circulation.

On the Campbell Uplift, immediately south of the airfield at the community of Inuvik, there is a similar, isolated patch of corridor and sinkhole karst that appears to be largely arrested by permafrost today.

7. Northern Mackenzie Mountains (Topographic Sheets 96D, 96E, 106A, 106G, 106H)

The principal features of interest are the Canyon Ranges with an extensive, extremely varied, and visually attractive range of karst landforms and groundwater phenomena that broadly can be described as lying along or close to either side of the existing Canol Heritage Trail. In his 2008 Report on the Sahtu karsts, the author recommended the integration and promotion of these features and the Canol Trail as a UNESCO International Geopark, with the potential for later nomination for UNESCO World Heritage status (Ford 2008, pp.135 – 231). The principal regional strata are the Franklin Mountain, Mount Kindle and Bear Rock dolomites, with some important redbeds with salt and gypsum below and the Hume limestone (northern equivalent of the Nahanni limestone) on top. The range of elevation is from 200 metres to nearly 2000 metres above sea level, giving rise to big contrasts in the ecozones and permafrost encountered along the Trail through the karst.

Amongst the many highlights of this terrain are:

i. the Plains of Abraham, a never-glaciated high plateau with a fine display of periglacial patterned ground landforms on Mount Kindle dolomite but with some spectacular springhead sapping karst groundwater cirques that create small oases in the barren tundra;

ii. the Moraine Polje, a never-glaciated valley to the south of the Plains, blocked by a terminal moraine ridge at its mouth that was deposited by the Laurentide Ice Sheet during its westward limit of penetration into the Mountains. The blocked valley is drained underground via a river cave that flows to a most spectacular spring bursting from cliffs downstream of the moraine dam;

iii. the Pyramid Lake Polje, on the Canol Trail, a large closed depression formed by a geologic syncline and drained underground to springs on the Little Keele River;

iv. the Dodo Dry Canyon, is the paleo-course of the Little Keele, which a recent glaciation diverted into the Caracajou River. The abandoned canyon has local sinking streams, spectacular screes, and exposures of paleokarst in dolomites;

v. the modern Dodo Canyon channels the Dodo Creek through a geologic anticline (upfold) that exposes all of the important regional strata in sequence in its vertical cliffs. The sequence begins with bright yellow siltstones and red shales, deformed by landslides and slumped blocks where underlying salt has been dissolved. Above it are the Franklin Mountain dolomites which weather bright orange and have attractive pinnacles among their cliffs. The Mount Kindle dolomite is grey in contrast, giving way to multi-coloured cliffs in the Bear Rock Breccia, before the Creek passes through bright white Hume limestone and into the Mackenzie Valley.

vi. the Mt Kindle strata, North of Dodo Canyon, are the most extensive dolomite solutional pavements known in the sub-arctic; they display a rich diversity of karren (karst) landforms;

vii. the Breccia on the south flank of the Dodo Canyon, by contrast, display a unique “drape karst” topography in which case-hardened upper layers of the Breccia are broken up by karst and frost action, and slide down the sides of big sinkholes into more weakly cemented rock below.

viii. the spillway at the eastern edge of the Mackenzie Moutains, a large river channel carved into the eastern edge of the mountains by a seasonal melt river from the Laurentide Ice Sheet, near the end of the last glaciations, cutting across the older courses of the Carcajou River, Dodo Creek, and other creeks, locally diverting them. Portions of this spillway are now highly karstified, including:
   a) the “Bonus Lake” and Grotto Mountain karst of solutional corridors, sinkholes, a ‘disappearing lake’ with beautiful shores, the grotto, natural bridges, etc.
   b) Carcajou Canyon, a 30 kilometre diversion of the River. There are many sinkholes in the Breccia and limestone on its eastern flanks.
   c) fragments of a relict (dry) spillway, northwest of Dodo Canyon, with more drape and pinnacle karst, small caves, and natural bridges that are finally buried by great debris fans of the Breccia from the Mountain front.

North of the Mackenzie Mountains themselves, the outlying Imperial Hills extend for 70 kilometres along the Mackenzie Valley, rising 300 to 500 metres above the valley. They are in the Breccia and Hume limestone and exhibit many karst features similar to those of

Bear Rock itself. They are another attractive and striking karst terrain that merits more detailed appraisal.

Significant Karst Terrains in the Northwest Territories

Criteria to gauge significance are:

1. the quality and interest of the karst landforms and the karst groundwater system development within the given region,
2. whether the individual landforms or their regional assemblages in the Northwest Territories are significant at the global scale, being either:
    a. good to very good examples of landforms and types of assemblages already known elsewhere that will contribute to our understanding of the generic development because they widen the range of rock types and/or environmental (climatic, ecologic) settings in which development is found to occur, or
    b. displays of landforms and/or assemblages that are new to karst geomorphic and hydrogeologic studies, or extend the range of known karst lands to geographic regions previously considered unsuitable for development of karst.

Applying the criteria –Areas of Established Global Significance:

i. The Southeastern Region has long been recognized internationally because of the protection and publicity given to Wood Buffalo National Park. The contractor rates it as "Significant" at the world scale because of the quality of the collapse sinkhole landforms and the simplicity of the hydrogeologic organization.

ii. The Low Plateaus and Hydration Ridges are rated "Very Significant" at the world scale because they incorporate an exceptional variety of landforms and hydrogeologic organization that is expressed in the three contrasted core areas: the Mahony Dome, the Tunago Dome, and the Lac Belot – Tunago Lake Breccia Karst and Hydration Ridges. Together these form a geographic assemblage that is unique in geomorphology.

iii. The mountain and high plateau-canyon karst lands of the South Nahanni region of the southern Mackenzie Mountains are "Very Significant" at the world scale, again displaying combinations of unique features plus outstandingly good examples of more standard landforms and hydrogeologic systems in a sub-arctic setting. All of the karst lands lie within the expanded area of the Nahanni National Park Reserve.

iv. The mountain and high plateau karst of the northern Mackenzie Mountains that is centred on the Canol Heritage Trail area and promulgated in the Ford (2008), is "Very Significant" at the world scale. It contains excellent examples of standard landforms that have developed in very adverse climatic settings, plus other landforms that are unique.

Territorial karst areas where the significance is not yet well established, but merits further study, include:

i. The Franklin Mountain Ranges, which were overridden by the Laurentide Ice Sheet. The head-on collision of flowing glacier ice with steep-fronted mountain barriers of carbonate rocks has created complex landscapes in which karst or surface stream action can prevail during interglacial times, glacier erosion with modification or destruction of all prior landforms during the glaciations. The Franklin Mountains are not rated here, because their more extensive southern sector, the McConnell Range, has not been studied any detail.

ii. The Sinking Streams (Fluviokarst) of the Horton River, which came as a big surprise to this author. There are a large number of streams sinking underground into what must be well established karst aquifers. Yet the environment is very hostile, cold, dry, with deep permafrost, strata that are the least soluble of the standard karst rocks, and low hydraulic gradients to drive the underground water circulation. A long record of inheritance is suspected, possibly pre-dating the in-growth of the permafrost. This area will be of substantial interest to karst scholars and groundwater hydrologists worldwide.

iii. The Imperial Hills are comparatively modest in their extent and elevation but appear to encapsulate many of the karst and other processes at work on the Bear Rock and Hume strata elsewhere, with active sinkhole formation, sinking lakes, turloughs, etc. They merit field study of the karst phenomena.

iv. The Horseshoe Lake Glaciokarst Depression, Iverson Range, a unique landform, warrants a field survey, which should also include the remainder of the Iverson Range.

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Table of Contents

1. Introduction

1.1. Editor's Note

1.1.1. This report includes references to paper maps created by Dr. Ford which include the delineation of karst areas of the NWT on paper 1:250,000 maps (or another scale), including *well known karst areas, and **lesser-known karst areas mentioned elsewhere but not yet investigated to any extent.

1.1.2. Digital maps were created using this information and are available in Appendix B and for download on the NWT PAS website (www.nwtpas.ca). The Notes, Area Numbers, and Sites referenced in this report are not included on these maps due to level of detail, however topographic reference points and map sheets are included. Copies of the paper map sheets created by Dr. Ford are being stored by the Protected Areas Strategy, Department of Environment and Natural Resources, GNWT. A data request can be made to the PAS at nwt_pas@gov.nt.ca for copies.

1.2. A Summary of the Geological and Geomorphological Background of Karst Landform Development in the Northwest Territories.

1.2.1. Karst Terminology

Globally, karst landforms and groundwater systems develop on the limited range of rocks that are slightly too strongly soluble in natural waters. As a consequence of this solubility, water is able to sink underground and develop **solutional conduits** through the rock between sinkpoints and springs, rather than flowing off in open stream channels at the surface. Flow through karst conduits can be much more rapid than it is through the pores or fractures underground in insoluble rocks, being generally in the range of many tens of metres to several kilometres per day. Where they become large enough for human entry, the conduits are known as **caves**. At the surface, sinking waters may create: patterns of small intersecting openings along fracture lines known as **karst pavements**, larger solutional **corridors** several metres wide (known as bogaz when only a metre or two wide), funnel-shaped or cylindrical-shaft **sinkholes** a few metres to tens or hundreds of metres in diameter, larger **blind valleys** that terminate in one or more sinks or **topographically closed depressions** that may have flat corrosional or aggradational floors, and, at the largest scale, **dry valleys and canyons**. A detailed summary of the variety of karst features and processes, with special reference to karst landforms common in the NWT, is presented in Ford (2008) pages 1-25. For comprehensive description and analysis of karst processes and landforms worldwide, see Ford and Williams (2007).

1.2.2. Karst Rocks

The principal karst rocks are:

1. Carbonates - **limestone and dolomite**: The solubility of limestone ranges from 100 to 400 milligrams per litre in most natural waters, with dolomite slightly less soluble. Globally, and in the NWT, these are the most widespread of the karst rocks.

2. Sulphates – **gypsum and anhydrite**: Gypsum has a solubility of 2000-2500 milligrams per litre in most natural waters, i.e. five to ten times as soluble as limestone. Anhydrite must hydrate to gypsum before finally dissolving.

3. Halites – chiefly **salt:** Their solubility is 350,000 mg/l in most waters so they rarely survive to be seen at the surface, except in extreme desert conditions. However, their dissolution beneath a protective cover of other kinds of rocks may induce collapse of those rocks through to the surface, which is known as **covered karst**.

4. **Quartz sandstones and quartzites:** May also yield some karst features under some circumstances, chiefly the pavement forms, bogaz, shaft sinkholes, and a limited variety of caves. Their solubility is five to ten times less than that of limestone but where they are also very strongly cemented, and thus resistant to the alternative mechanical processes of erosion, solutional forms can prevail locally. For more information, see Ford and Williams (2007).

1.2.3. Rocks in the Northwest Territories

All of the important types of karst rocks are present in abundance in the Northwest Territories, between the Shield in the east and the western (Ragged) ranges of the Mackenzie Mountains in the west. In fact, the Territories contain the most extensive continuous belts and tracts of karst terrain known anywhere in Canada. Most of the karst rocks are Paleozoic in age. The oldest of them are salt, gypsum, and anhydrite intermixed with layers (beds and thicker units) of dolomite, shale, siltstone, and/or sandstone in the Cambrian (basal Paleozoic) strata. There is also visually striking sandstone in the Cambrian, the Mount Cap Formation (Formation). Overlying these are very extensive spreads of dolomites of Ordovician and Silurian age that accumulated to substantial thicknesses on broad and shallow marine platforms. Above them in the southeast are sequences of gypsum, dolomite and limestone accumulated behind (south of) large barrier reefs that now front the southern shore of Great Slave Lake; they are Devonian in age. In the southern Mackenzie Mountains the Silurian dolomites are succeeded by the Nahanni Formation (Devonian), a very important karstic limestone. In the northern Mackenzie and Franklin Mountains and in the plains and plateaus west and north of Great Bear Lake, the Nahanni limestone is replaced by the very significant Bear Rock Breccia (dolomite and gypsum) overlain by a lesser limestone (Hume Formation) and then sequences of shales and shaly (impure) limestones that are not often suitable for karst development. After deposition of the shaly limestones, there was a long period of erosion over the entire area, following which insoluble shales, siltstones, and sandstones of Cretaceous age were laid down to bury the surviving older rocks. This cover is now largely stripped away in the mountains but persists over large parts of the plains and plateaus. Where pertinent, details of individual karst formations are given in the Regional Notes below.

1.2.4. Geomorphology

The development of karst groundwater flow and landforms in the Northwest Territories differs quite significantly from development in most of the rest of the world. In tropical and southern temperate regions, solution processes have only to compete against the fluvial and hill slope surficial processes that seek to drain the water away above ground. All of the Northwest Territories, except a narrow corridor in the Mackenzie Mountains, have been repeatedly covered by flowing glacier ice that could scour away or infill any pre-existing karst features or, alternatively, accelerate their enlargement by injecting subglacial meltwater into them. Most karst terrains in Canada have a similar history. In general, glaciation has had negative effects. Any subsequent karst evolution is slowed down or suppressed into geographic patterns that can be highly irregular because they are influenced by past glacial erosion and/or deposition. As a consequence, almost all of the areas considered in this report may have a complex mixture of 'inherited' effects and landforms as well as postglacial forms. This is why 'fresh' collapse and funnel-shaped sinkholes that have developed since the last ice receded ('postglacial') stand out from most other karst forms in the region and are those most likely to be noticed and reported by non-specialists. See Ford 2008, for more details.

A further complication is that the upper few meters to tens of metres of the ground has either widespread or continuous permafrost in the Territories, north of Great Slave Lake. Existence of frozen ground below the seasonally melted uppermost metre or so places restrictions on the maintenance of groundwater flow deeper into the rock and will inhibit inception of new karst water circulation through what are, initially, narrow fractures. As we proceed northward across the Territories, permafrost restrictions become increasingly important, and the number of sites where it appears that ancient karst areas have been rendered inert by ground freezing increases. See Ford 1983, 1987, and 2008 for details.

1.3. The Economic and Social Significance of Karst Landforms and Groundwater

1.3.1. Global Significance of Kart Groundwater and Rock

Globally, some 20% of the world's population is partly to entirely dependent on karst groundwater for its water supplies, including most of the rural American population east of the Mississippi River, most of the population of Egypt, and over 200 million people in southern China. Limestone and dolomite are the world's most mined and quarried rocks for building stone, cement, highway aggregate, and they host about 50% of the known reserves of oil and gas plus as well as major mineral deposits. As a consequence, their economic significance worldwide is to be counted in the trillions of dollars annually. However, this is of less significance in the Northwest Territories because of the abundance of alternative water resources and a limited demand for cement and aggregates.

1.3.2. Tourism

Karst landscapes and natural caverns have powerful tourist appeal. There are more than one thousand tourist caves open to the public worldwide (with over 400 in China alone). The attractions at these caves can include spectacular displays of stalactites and stalagmites, roaring underground rivers, giant chambers, and specially adapted fauna such as blind fish. It is estimated that the gross tourism earnings of these caves probably exceeds one billion dollars annually.

In general, the current potential for development of tourist show caves is considered to be low for the Territories. Caves in the NWT tend to be small in height and width (though not necessarily in length), cold, and restricted to few and small displays of stalactites and stalagmites. In addition, access to the best examples that are known in the Territories (i.e. in the South Nahanni) is difficult and costly. However, caves with cold, still, and stable air and that have been abandoned by their formative groundwater, can favour the deposition of beautiful displays of ice crystals. These can grow to sizes much larger than are seen above ground and can accumulate in great masses. In the Alps, Carpathians, and Ural Mountains in Europe there are a handful of economically successful ‘ice caves’ that draw thousands of visitors each year. A discovery of one or more example of such a cave, near to a community in the Territories is quite possible and could be of touristic appeal.

The chief tourist potential of the karst in the NWT at this time lies in the many spectacular displays of landforms at the surface, chiefly pavements, sinkholes, sinking lakes, drape karst, dry valleys, and canyons. The greatest concentration of these known to the author, outside of South Nahanni National Park, are found astride the Canol Heritage Trail and the surrounding area in the Mackenzie Mountains, between the Plains of Abraham in the west and the mouths of the Carcajou and Dodo river canyons downstream to the east. If these features were within a more densely peopled region, such as Europe, they would be attracting tens to hundreds of thousands of visitors per year. They are described in detail in the Ford (2008), pages 135-231.

1.4. The Scientific and Conservation Significance of the Karst Landforms and Groundwater Systems in the Northwest Territories

1.4.1. Sub Arctic to Arctic Karst and Global Warming

The Northwest Territories is considered, by this author, to be a key site for the fundamental study of karst landform and groundwater evolution in sub arctic to arctic conditions and the study the effects of global warming. In our present state of understanding, it can be written that the NWT probably contains a greater extent of karst topography and drainage in a sub-arctic to arctic setting than any other region on Earth. The only uncertain competitor is northern Siberia, where there have been very few studies, however it is unlikely to have developed such a strong karst system as most of Siberia was never glaciated and has wider and deeper permafrost than in the Territories.

The NWT is also a key site for the study and monitoring of impacts of global warming in the vulnerable northern continental interior areas. With the expected melting of permafrost from global warming, this is would accelerate the rate of expansion of areas being drained underground with concurrent increase in karst displays, such as abrupt appearance of new collapse sinkholes and desiccation of drainage basins.

1.4.2. Conservation

The NWT is also a vital component in the broader karst conservation perspective. The recognition of the presence of karst and the categorisation of the types of karst in a given locality is important from broad conservation principles. For example, the Ford report (2008, pages 47-98) defines the natural evolution of 'turloughs' (shallow karstic basins) during the post-glacial. Over quite a short time span these may progress from (i) permanent lakes draining externally at the surface, to (ii) permanent lakes draining underground to karst springs, to (iii) seasonal lakes, drying out in the summer, to (iv) desiccated basins drained by multiple sinkholes. The processes can move quite swiftly because the drainage systems are delicate and fragile. It is predicted that this process will accelerate in times of global warming.

1.4.3. Unique Biology

Karst terrains also have the potential for unique ecological assemblages, in particular vegetal, because of the peculiarities of their drainage underground. In glaciated regions, the best known examples are of 'alvar' assemblages on limestone and dolomite pavements. The term is Swedish, from the island of Gotland, which is a limestone plain. Alvars develop where the land is very flat so that groundwater hydraulic gradients are low but it can nevertheless be drained largely or entirely into a shallow 'epikarst' consisting of small solutional channels extending one or a few metres down into the pavement. The vegetal association reflects a combination of the stresses of prolonged inundation during the spring thaw and of drought later in the summer.

In addition, the ecology of gypsum or dolomite/gypsum breccia karst areas can be expected to differ from those on ordinary limestone or dolomite. These will vary with elevation, especially around treeline altitudes, and will differ from those found on non-karst rocks. It is expected that in the NWT, with its thousands of square kilometres of karst aquifers, there could be many new species of underground-adapted fauna to be found. However, our knowledge of these communities is limited as there have been very few published studies to date. In addition, the author is not aware of any current searches being done by others. As a result, the NWT contains a new karst geographic sub-field with significant potential from the perspective of evolutionary studies.

It is important that these unique, rare and/or new ecological assemblages be investigated. All karst aquifers can be described as fragile, prone to rapid and serious contamination, for example, as was the case in Walkerton, Ontario. The karst of the NWT is expected to be especially vulnerable due to the low temperatures and consequently low rates of biological activity.

2. Methods and Limitations

2.1. Mapping Scale and Map Selection

The area of the Northwest Territories where karst landforms and processes may occur is very large. Given the scope of this contract, it was agreed that preliminary recording on 1:250,000 scale maps was appropriate. At this scale all notable clusters of karst features can be plotted and the larger individual landforms can be outlined, although there cannot be precise geographic locations because of the coarseness of the scale. Mapping at a scale of 1:250,000 is preferred to the reduction and generalization of phenomena at 1:500,000 or 1:1,000,000 scales, while also indicating where more detailed investigation and plotting on 1:50,000 maps, at a larger scale, is warranted.

All the 1:250,000 map sheets covering the broadly favourable karst terrain between the Canadian Shield and the Ragged Ranges of the Mackenzie Mountains were inspected first. A few sheets were rejected at this stage because there was little or no karst rock in outcrop or shallow sub-crop on them and/or the topographic relief was too flat to likely support significant modern karst groundwater circulation. Sample transects of Google Earth and Landsat images were used as supplements at this stage.

All remaining sheets of interest were ordered from World of Maps, Ottawa, for data plotting. They are listed in National Topographic Survey (NTS) order in Appendix A. On the basis of the preliminary selection they were then divided into two categories:

(1) known or likely to contain significant or potentially significant karst. All suitable terrain (for example, karst rocks present or terrain not entirely low gradient muskeg) on these sheets was surveyed by stereoscopy with air photo pairs.

(2) unlikely to contain notable karst but the possibility cannot be dismissed entirely. These sheets were sampled by air photo traversing along sample transects only.

2.2. Air Photo Analysis

The air photo analysis was undertaken at the National Air Photo Library (now Geomatics Canada), 615 Booth Street, Ottawa, ON between the period September 8 to12 2008. The author would like to thank the staff of the Library for their courtesy and helpfulness at all times.

The preferred photo scale selected for use was 1:50,000 (approximately one inch to the mile). This was the scale used to draft the 1:50,000 national topographic map series. As a consequence, the coverage is better than at other scales and the quality of the images is more uniform. At this scale quite small sinkholes can be detected and larger patches of karst pavement (the smallest scale landform) can be recognized. Precise location of stream sinkpoints and karst springs is difficult to establish, however, especially where there is forest cover.

In the Northwest Territories there is little stereoscopic coverage at larger scales except in areas of special economic interest such as the proposed Mackenzie Gas Pipeline corridor and the Diamond Mines, or around communities. Study of large scale photography (e.g. 1:20,000) was infeasible because of this as well as time limitations at the Library.

Recognition and plotting of karst features was done using conventional air photo stereoscopic methods, with equipment supplied by the National Air Photo Library. The contractor has previous experience with stereoscopic studies of karst terrains worldwide.

2.3. Confirmation with 1:50,000 Topographic Maps

Where the air photo analysis suggested the occurrence of karst features that were difficult to determine because of low relief (for example, large but very shallow closed depressions, especially where forested, or streams that might be sinking underground but that also overflow during melt periods) the author's interpretation was confirmed against the independent interpretations of the cartographers who had, in most cases, used the same series of photographs to draft the national 1:50,000 topographic map series. The relevant topographic maps were inspected in the Lloyd Reeds Map Library at McMaster University, which has a complete set of the national 1:50,000 series maps.

It should be noted that it is this author's experience that generally the national cartographers are reluctant to identify karstic phenomena. If their maps indicate karst, for example, a sinking stream, then sinking certainly occurs at that location and is likely also happening to nearby streams that are mapped as flowing at the surface. The author can guide interested persons to many places in Canada where cartographers have had streams flow uphill rather than have them flow underground.

2.4. Other References

The air photo and cartographic analysis was both guided and supplemented by review of Geological Survey of Canada geological maps, published and open file reports, reports of the National Hydrological Institute, relevant published scientific journal papers and notes, and references in books, as set out in the List of References in this Report.

2.5. Limitations and Areas for Further Study

2.5.1. Limitation with the Study Design

The principal limitation in this research is the scope of the Contract, which supported four to five days of air photo analysis at the NAPL in Ottawa and no ground truthing in the Northwest Territories. A comprehensive survey of this kind would require forty person days or more, with a concomitant increase in cost.

Another limitation was sampling design. As noted previously (see Section 2.1), terrains judged to have little potential for significant karst in the preliminary review were not fully covered in the air photo survey, but sampled along selected transects instead. It is therefore quite possible that some interesting and significant features were missed.

In addition, as previously noted, the 1:50,000 scale air photographs do not allow for high resolution of small landforms or the detection of small stream sinks. The presence of small sinkholes (less than 20 m in diameter under forest cover, less than 10 m on open ground) will be missed unless they are very fresh. Entrances to explorable caves can rarely be detected from air photos, even with very large scale photos. To increase the difficulty in some areas, a few of the air photos were of poor quality (blurred) so that small features could have easily been missed on those photos. Fortunately this was rare.

An especially important point is that it is difficult to detect karst springs with confidence unless they are both large in volume and conspicuous in position (e.g. gushing out of an open cliff face, as one spring is in the Nahanni country). Therefore, no attempt has been made to map unreported springs in this Report. All that are shown are known because they have been published or reported to the contractor directly. Lack of knowledge of the location of springs is particularly unfortunate because their locations and volumes of discharge will tell karst specialists a good deal about the nature, extent, and maturity of the groundwater systems draining into them. Arising from a lifetime of experience working on karst, the author can estimate the broad location of springs for many of the sinking streams but considers it prudent not to include them on the maps.

2.5.2. Areas That Could Use Further Review

1. **Gypsum Terrains:** Time did not permit careful study of some gypsum terrains along the north shore of Great Slave Lake between Sulphur Bay and Russell Lake. There may be attractive sinkholes and forms of lesser scale (such as lake shore corrosion notches) in places that would not be very apparent on the 1:50,000 photos.

2. **Shield Rocks:** There are small outcrops of dolomite in the Shield rocks around Christie Bay at the east end of Great Slave Lake, and south of Dease Arm in northeast Great Bear Lake. These are Proterozoic or older in age and may be partly metamorphosed which tends to reduce their already low solubility. The author knows of no current reports of significant karst features in them so they were not included in the air photo survey.

3. **Alvars:** Alvars are vegetated pavements with particular ecological assemblages associated with limestone and dolomite solutional pavements. See Section 1.4.3 for more information on alvars. Unless they are very extensive and strongly developed it is difficult to detect the pavement through the vegetation cover. The author lacks the specialized skill to recognize them on small scale, black and white air photos although he does have experience detecting them with 'false colour' non-stereographic imagery on Anticosti Island, Quebec. In this Report, the only alvars plotted are those reported to the author by Robert Decker (Environment and Natural Resources, GNWT) and Paul Catling (Agriculture Canada).

2.6. The Key to the Maps

As the air photo and map scales used in the work are small, the number of symbols used has also been kept small and simple. Additional information on various landforms follows.

2.6.1. Sinkholes

The ‘sinkhole’ symbol is generally larger in extent on the map sheet than most actual sinkholes. It indicates the presence of one or more sinkholes in the area but is not a precise location. However, the ‘sinkhole of exceptional interest’ symbol is centred as closely as possible, given the map scale, over the feature; they are usually large, sharp, and fresh in appearance on the photo and will be mentioned in the accompanying notes. The ‘cluster of sinkholes’ symbol represents a location with a density of more than one sinkhole per square kilometre and with a maximum in the range of 10-100 sinkholes per square kilometre. The ‘sinkhole more widely scattered’ symbol represents areas where there are fewer than one sink per square km on average; these sinkholes are at such low densities that the individual sinkholes are not likely to be integrated into simple underground drainage patterns but rather indicate partial inheritance in glacially modified karst terrains or a collapse at random points. The ‘sinkhole more widely scattered’ symbol is once again indicative and does not represent the precise geographic location of a sinkhole.

2.6.2. Depressions

The size and outline of the large, topographically closed, depressions are approximately accurate in shape. The central water sink point or points will fall within this boundary.

2.6.3. Solutional Pavements

Karst features generally less than 10 m in their greatest dimension (e.g. length of a solutional grike) cannot be detected but, where they intersect each other in patterns that cover much larger areas, they are plotted as ‘karst solutional pavement’. In the areas studied they could not be detected with confidence where forested, so that mapped pavements are limited to displays in the shrub and tundra botanical zones. It is certain that there are extensive tracts of pavement beneath the extensive forest cover on limestone and dolomite outcrops.

2.6.4. Solutional Corridors

Karst intersecting solutional corridors refers to patterns of solutional enlargement along joint fracture patterns that are larger than those occurring on pavements. They are usually at least several metres in width and depth and tens to hundreds of metres in length. Like pavements, they intersect to create more extensive spreads. Such assemblages are known elsewhere in the world but they are unusually widespread in the NWT where, at least in part, they are thought to be created or enlarged by sub-glacial flood bursts.

2.6.5. Caves

As discussed previously in Section 2.5.1., the presence of caves of sizes that can be entered by humans cannot be detected on air photographs. Those indicated on the maps have been explored on the ground and reported or, in a few instances, observed by the author at a close range in which they looked promising.

2.6.6. Pinnacles

The Bear Rock breccia at several locations displays distinctive ridges or clusters decorated with a numbers of sharp bedrock pinnacles that are several to many metres in height. This pinnacle karst has been plotted where observed. Lesser pinnacles will have been missed at this mapping scale.

2.6.7. Tors

Tors develop on the tops of mountains and along ridges on many different rocks. The finest forms are usually on massive and resistant limestones, dolomites, and quartzites, all of which display some karstic solution along bedding plane and joint fractures within them. Those mapped in this work are tens to hundreds of metres in length and five to fifty metres in height.

2.6.8. Sinking Streams or Rivers

The approximate location of the apparent sinkpoint of a sinking stream is indicated by the tip of the arrow in the symbol. However, it is generalized. In many instances a stream will overflow for tens to hundreds of metres or more during floods and may discharge some proportion of its flow entirely at the surface. In a similar manner, there are a large number of streams in the karst areas that will lose a portion of their flow underground throughout the active season but maintain some surface flow and thus, on the air photos, appear to be entirely non-karstic.

2.6.9. Springs

As previously noted in Section 2.5.1, because of the difficulties in detecting springs on conventional small scale air photos, only those spring reported in publications or observed by the contractor have been shown.

2.6.10. Underground Draining Lake or Pond

There are many ponds and even large lakes in the territorial karst areas which appear to have no surface outlets or even peripheral sinkpoints. Many show evidence of large seasonal fluctuations in the water level that suggest slow seepage away underground through glacial or other detrital fill in the bottom of an old sinkhole. There were simply too many small to very small examples of these detected in the photo survey to be plotted individually; they are included with the dense or scattered sinkhole categories. In addition, a majority of the large examples were not plotted because of some uncertainty; e.g. they might be draining via small surface channels masked by forest. It is acknowledged that this category of features has probably been under-represented to a substantial degree in the mapping.

2.6.11. Alvars

As previously noted in Section 2.5.2., the author is not qualified to detect alvars or probable alvars on black and white, small scale air photographs. Those shown are plotted from personal reports.

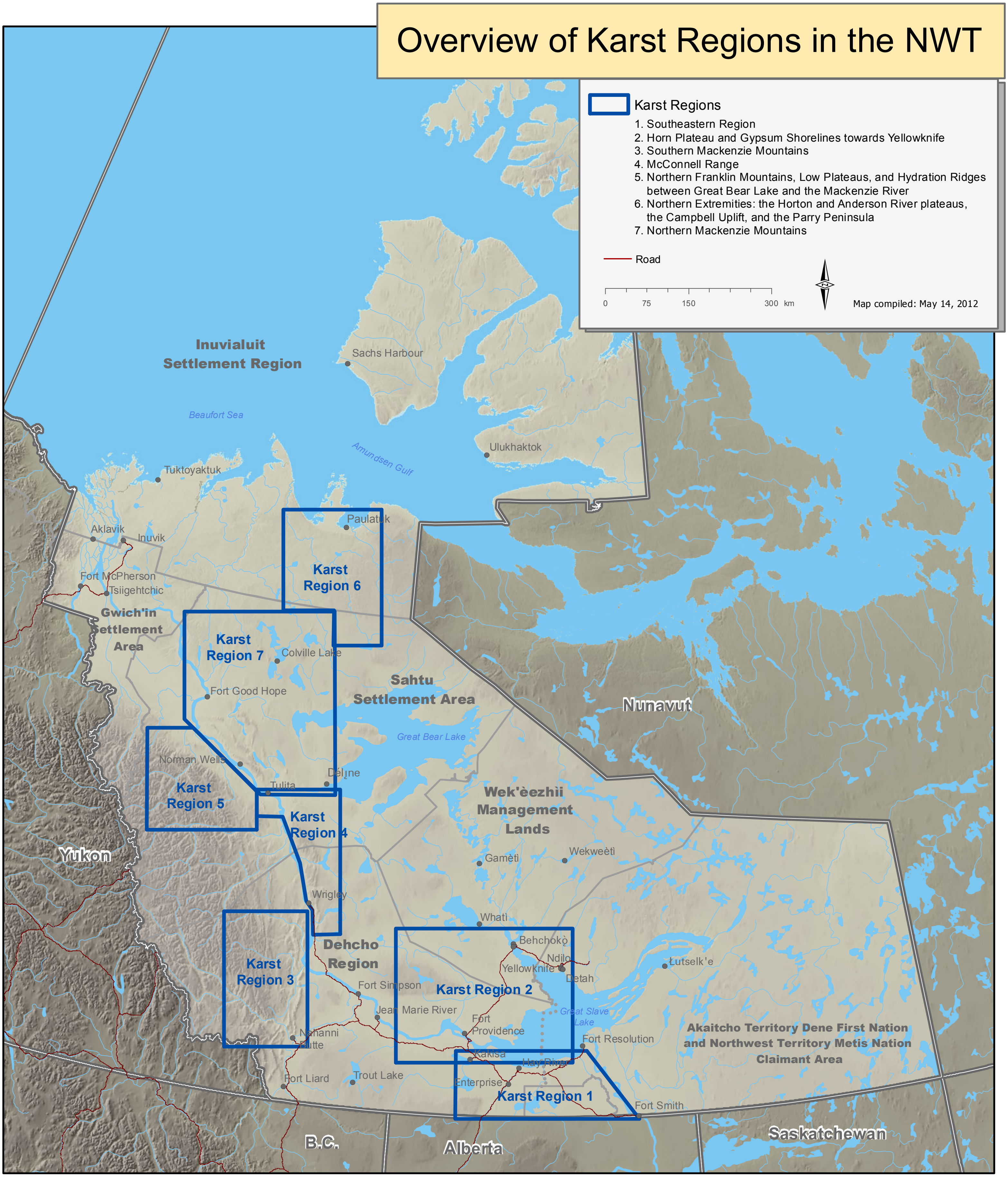
3. Karst Regions of the Northwest Territories, with Notes on Features on Individual 1:250,000 Map Sheets.

A total of thirty eight 1:250,000 topographic map sheets of the Northwest Territories were studied during the course of this project. Based on a combination of geologic and geomorphic criteria they have been grouped into the seven different regions considered below:

1. Southeastern Region,
2. Surrounds of the Horn Plateau and Gypsum Shores towards Yellowknife,
3. Southern Mackenzie Mountains,
4. McConnell Range of the Franklin Mountains,
5. Northern Franklin Mountains,
6. Northern Extremities, and
7. Northern Mackenzie Mountains.

A map of these seven regions can be seen on the next page. In a few instances one particular map sheet contains features from two different regions, but the overlap is not considerable.

Overview of Karst Regions in the NWT



3.1. Southeastern Region

3.1.1. General Description of the Region

The southeastern region extends from the Territorial border at 60^o N latitude at the Slave River, northwards to the shores of Great Slave Lake, and westwards to the Kakisa River. It includes parts of 1:250,000 sheets 85A Klewi River, 85B Buffalo Lake, 85C Tathlina Lake and 85D Kakisa River. A map showing the karst features in the Southearstern Region can be seen in Appendix B.

Much of this region is underlain by Paleozoic rocks of Devonian age but they are widely masked by glacial and other unconsolidated detrital deposits. There are higher plateaus to the west and south on Cretaceous clastic rocks. On the Paleozoic rocks, the most extensive gypsum karst and gypsum cap-rocked karst lands known on the North American continent extend across Sheets 85A and 85B and southwards into northern Alberta. The topography is of low relief, comprising an upper, generally flat, and swampy plateau that is separated by minor and discontinuous low escarpments from a lower flat and swampy plain at or close to the elevation of the Slave River, which is the regional base level for drainage.

The upper plateau is formed on limestones and dolomites, plus calcareous shales and argillaceous limestones, which are impure rocks from a solubility perspective and thus unsuitable for good karst development. These are grouped into the Slave Point and Hay River geologic formations and are underlain by more pure and interbedded limestones, dolomites, gypsum, and anhydrite of the Nyarling Formation. Dissolution in the Nyarling creates small but prominent hydration ridges and blisters. There are many sinking streams. Solution cave collapse extends up into the Slave Point and, more rarely, into the Hay River strata to form collapse sinkholes. In an early review, Drake (1970) divided the sinkholes into two broad categories:

(i) More than 20 metres in diameter: These sinkholes are near-circular collapse, through the limestone or dolomite cover, into gypsum underneath, usually with vertical cliffs at the top, descending on carbonate talus to ponds at or a little above the top of the gypsum. Some caves can be entered in the cliffs and followed for as much as 400 metres and they display a 'breakdown' morphology (fallen roof blocks) typical of gypsum caves in Canada. An example is the Walkin Cave described in Tsui and Cruden (1984).

(ii) Less than 20 metres in diameter: These sinkholes have the shape of funnels and have formed chiefly within overlying glacial debris, signalling the collapse or piping of the debris into solution caves underneath.

Drake (1970) estimated that there were more than 2000 sinkholes of these types on the plateau within Wood Buffalo National Park.

The Nyarling Formation that creates the most of the karst features on the plateau is underlain by the Keg River Formation, ~60 meters of limestone and chiefly dolomite that is regularly bedded. These strata rest on the Chinchaga Formation which, formally, comprises a total of approximately 80 meters of gypsum and anhydrite underlain by dolomites and the Cold Lake Salt formation. However, in many areas on the Klewi River sheet, the gypsum has been largely or entirely dissolved away, undermining the Keg River rocks which have foundered as broken masses of differing sizes. On the Slave River plain these are mostly buried by glacial and fluvial sediments supporting swamps. Where streams are noted as sinking (Sheet 85A), they are probably passing into cavities in the foundered strata that are below the water-table. There are many springs rich in sulphate along the scarp foot, some of which also have abundant salt.

The most prominent and well-known karst landforms are within Wood Buffalo National Park, in both the NWT and Alberta parts. As these have been described in reports by Parks Canada, theses, and journal papers (e.g. Moset et al. 1998 and Soper 1939) they were not considered in this Report. In addition the Wood Buffalo type of karst lying immediately outside of the Park in the Northwest Territories was not mapped in detail in order to save time for the lesser-known and unprotected karst areas elsewhere.

Notes on particular features or sub-areas numbered on the map sheets are given below.

3.1.2. Specific Description of Features and Areas

3.1.2.1. Sheet 85A – Klewi River

In Area 1, there are sinking streams, sinkholes, and a large closed depression adjoining Salt Mountain, plus extensive efflorescences of salt at the Keg River scarp foot along Lobstick Creek and Little Buffalo River. Because these features are quite prominent and Highway 5 passes through the area, some interpretation and display is merited, if it is not already present.

In Area 2, there is a north-west-trending belt of scattered sinkholes that is an extension of the main plateau belt formed on the Nyarling Formation within the National Park. Fresh collapse sinkholes are prominent in the southern half of the area and the smaller funnel sinks further to the north.

3.1.2.2. Sheet 85B – Buffalo Lake

Sinkhole Area #1 denoted on this sheet is the northerly end of a second prominent belt of sinkholes within the National Park. It includes typical Type 1 fresh collapse sinkholes with cliffs and ponds.

Hanbury Creek heads in a group of karst springs. There are some twenty sinkholes of both types, plus foundered terrain, in an area of 12 km^2 around the springs. Collapse sinkholes measure up to 120 m in diameter and 60 m in depth in this area. There are also circular ponds of similar diameter that are probably inundated sinkholes (D.H.Adams, 1979; personal communication).

The former Pine Point Mines property covers an area of 48 km by 10 km extending from the Buffalo River eastward to the shore of Great Slave Lake. It is situated on a large reef structure of Devonian age termed the Presqu'ile Formation. This reef enclosed an immense lagoon to the south in which the Nyarling River, Keg River and other formations accumulated. To the west, the reef passes under the shaly rocks of the Hay River Formation and karst features largely disappear. Today the old reef is much eroded by glacial scour and buried beneath 1-5 m of stony glacial till. Modern karst features are limited to small solution pits and runnels (karren) on occasional outcrops and a few shallow, ring-like closed depressions where the glacial cover sediments have evidently settled into unconsolidated, much older fillings in paleokarst cavities below.

Pine Point is chiefly of interest as a paleokarst phenomenon. Paleokarst refers to karst assemblages (usually sinkholes, larger depressions, or caves) that have become buried and rendered inert (i.e. there is no longer significant circulation of groundwater through them and dissolution has come to a halt). The Pine Point features are a series of filled caves scattered at different elevations along the old reef front, with large filled collapses above them in places that will have been open sinkholes in their day. They date to the Devonian geological period and were in-filled and buried as the reef sank by the local equivalent of the Hay River shales. Later, economic concentrations of zinc and lead accumulated in the fillings, which functioned as geochemical sieves for mineral-rich fluids flowing through them. Rhodes et al. (1984) have written the principal account of the geology and the paleo-caves and sinks in this area. Their interpretations are somewhat out-of-date. The caves and sinks probably formed in fresh-salt water mixing lenses along emergent reef fronts, and the sinks formed when collapses occurred above the water table due to loss of buoyant support. A most interesting point is that some of the long dead sinkholes were revived during episodes of glacial cover because there are some instances where glacial tills older than those of the last glaciation pass down through the Devonian age collapse fills. New collapse and filling was induced under the glaciers, probably as the land rebounded beneath thinning ice masses. Pine Point is one of the most extensive and complex examples of paleokarst known in North America; see Ford (1987), Ford and Williams (2007), pages 25 and 419.

3.1.2.3. Sheet 85C – Tathlina Lake and Sheet 85D – Kakisa River

The potential karst rocks on these sheets are coral lenses, reefs, and platformal limestones and dolomites (the Escarpment Falls, Alexandra Falls, Twin Falls and Grosmont formations) that inter-tongue with shales and limy shales of the Hay River Formation and other similar formations. They form a discontinuous escarpment facing Great Slave Lake. The plateau behind (to the south) has very low relief and is covered with glacial drift, so it exhibits little karst. The Cameron Hills rise above it, being a thick cover of clastic rocks (shales, siltstones and sandstones of Cretaceous age) that are insoluble. It is significant that none of the innumerable streams flowing off of the Hills appear to sink underground into the karst rocks once they reach them, due most likely to the combination of shales in the carbonate rocks, glacial drift cover and low relief, as previously noted.

Instead, there are striking river gorges with retreating waterfalls and rapids where the larger streams flow over the escarpment, e.g. Alexandra Falls. Karst appears to be largely limited to extensive but shallow spreads of limestone pavement. Some of these display excellent alvar assemblages. Alvars noted on this sheet are mostly along the Mackenzie Highway because of the ease of access to them but they will certainly be more widespread. As previously noted in Section 2.5.2., it is difficult to detect them on the small scale, black and white air photos used in this survey.

3.2. Surrounds of the Horn Plateau and Gypsum Shores towards Yellowknife

3.2.1. General Description of the Region

This region includes the area from the Horn Plateau east of the Mackenzie River, east along the north shore of Great Slave Lake to Yellowknife. It includes parts of 1:250,000 sheets 85E Mills Lake, 85L Willow Lake, 95I Bulmer Lake, Sheets 85G Sulphur Bay, 85J Yellowknife and 85K Rae. A map showing the karst features in the Surrounds of the Horn Plateau and Gypsum Shores towards Yellowknife Region can be seen in Appendix B.

3.2.2. Specific Description of Features and Areas

3.2.2.1. Sheets 85E – Mills Lake, 85L - Willow Lake and 95I – Bulmer Lake

These sheets cover the Horn Plateau and its surrounds. The Plateau is an upland in the Cretaceous clastic (non-karstic) rocks like the Cameron Hills. It parallels the Mackenzie River north and west of the mouth of Great Slave Lake, extending between Latitudes 61^{o} 50’ and 62^{o} 30’ N and Longitudes 118 and 121^{o} W.

The plains surrounding the Plateau are underlain by limestones, dolomites, and gypsum in many places but these bedrocks are deeply buried by glacial, lake, and river deposits for the most part. The topographic relief is low and there is much muskeg. Karst development is not favoured by such conditions. Geological reports mention a few possible sinkholes or (very shallow) closed depression features but without details. There are most likely a substantial number of karst springs in the muskeg around the foot of the Plateau but they cannot be detected with confidence on small scale photos, as previously noted in Section 2.5.1.

Area #1 on the Mills Lake sheet contains two sinking streams. The sinkpoints have very low relief so it is not apparent whether the sinks are into bedrock or into muskeg that, perhaps, has settled over melting ground ice. On the lower slopes of the Plateau, as these streams pass through there is some clustering of small ponds without surface drainage that might be drift-blocked karst ponds. However, they do not appear to be of substantial karst hydrological or geomorphic importance.

3.2.2.2. Sheets 85G – Sulphur Bay, 85J – Yellowknife and 85K – Rae

These sheets contain a number of areas where gypsum is the surficial bedrock or is only shallowly covered by dolomite beds. Once again, there are substantial depths of glacial, lake, and river deposits burying these bedrocks in most places but there is some exposure along the shores of Great Slave Lake at Gypsum Point and further north in the North Arm-Marian Lake area. The author has found no reports of karst in this region and found none on a sample air photo traverse. However, there are likely to be some attractive displays of small-scale gypsum coastal karst. Further studies are warranted here, as previously noted in Section 2.5.2.

3.3. The Southern Mackenzie Mountains

3.3.1. General Description of the Region

From the perspective of karst features within the Northwest Territories, the southern Mackenzie Mountains may be said to extend from the border at Latitude 60^o N to the Redstone River at Latitude 64^o N. They rise to 1500 – 2000 m above sea level. The mountains with some outcrop of the karst rocks occupy part or all of 1:250,000 topographic sheets 95B Fort Liard, 95F Virginia Falls, 95G Sibbeston Lake, 95J Camsell Bend, 95K Root River, 95M Wrigley Lake and 95N Dahadinni River. A map showing the karst features in the Southern Mackenzie Mountains Region can be seen in Appendix B.

The mountains form a series of ranges trending southeast to northwest, with the trunk river drainage cutting discordantly across from west to east until it reaches the Mackenzie River. The eastern ranges, termed the Canyon Ranges, are in Paleozoic sedimentary strata that were thrust up into spectacular series of east-facing, narrow-crested folds and overthrusts, plus some broader domal upfolds (anticlines) with downfolds (synclines) in between. The deformation was a result of the injection of large masses of igneous rocks (plutons) from the sub-crust during Cretaceous times; the plutons and associated rocks are now exposed as the Ragged Ranges that extend west into Yukon Territory.

The significant karst rocks are limited to limestone and dolomite in the southern Mackenzies, in contrast to the northern Mackenzies where interbedded gypsum is almost as important as it is in the Wood Buffalo karsts. The principal rock is the Nahanni Formation (Middle Devonian), which consists of 180-200 m of thick to massively bedded (mechanically resistant) and very pure limestone. It is a nearly ideal karstic limestone, with regularly spaced bedding planes and fractures to channel water through the strong but soluble rock. As a result, the finest caves yet known in the Northwest Territories are found in this region. It is also overlain by thick shales that supply water for sinking streams.

In the easterly Canyon Ranges, the Nahanni Formation is underlain by more than 1000 metres of thick to massively bedded and strongly colour-banded dolomites, the Arnica and Manetoe Formations (Middle Devonian). Karst sinkholes develop quite readily on these rocks (though not as frequently as on the limestone) and they are known to channel water to major springs via substantial, though inaccessible, cave passages. In the westerly Canyon Ranges, these dolomites are replaced by thinner, less pure, and mechanically weak dolomites and dolomitic shales of the cheerfully titled Headless and Funeral Formations. In the most easterly Canyon Ranges, older dolomites with lesser limestones and shales predominate. They support little karst.

3.3.2. Specific Description of Features and Areas

3.3.2.1. Sheet 95B – Fort Liard

The Liard Range occupies the westerly quarter of the sheet, overlooking the Liard River and plateaus on the Cretaceous clastic rocks to the east. The Range is narrow and sharp-crested, an overthrust in which all strata dip very steeply. There is some Nahanni limestone but the steep dip appears to have prohibited karst development to a significant degree. A few possible small sinkholes were noted on air photos but their identification is uncertain. There are no reports of karst or caves from this sheet.

3.3.2.2. Sheet 95F – Virginia Falls

This sheet includes the principal features of the celebrated South Nahanni Karst, which is certainly amongst the finest reported in the arctic and sub-arctic regions of the world. All of them are either within the present Nahanni National Park Reserve and the newly announced expansion of the Park. They will be summarized in brief here. There are full reports on karst in the Nahanni National Park by Parks Canada (1974, 1975 and 2007), the Nahanni National Park Reserve Resource Description and Analysis (1984) (to which the author contributed the chapters on geology, geomorphology and hydrology), the PhD thesis of G.A. Brook (1976) and other papers arising from this work that are listed in the References..

Most of the karst is developed in the Nahanni Formation but there are quite large but widely scattered sinkholes where the underlying Arnica and Manetoe dolomites are exposed to the north of First Canyon. These strata drain the southern half of the main Nahanni karst belt to the largest springs known in the region, White Spray (WS on the annotated map), in First Canyon.

In Area #1, the principal karst extends as a belt between First Canyon and the Bubbling Springs (BS) at the southwest corner of Ram Plateau. In 2006, groundwater dye tracing determined that White Spray drained all the water flowing into Canal Canyon (CC), Death Lake (DL) and lesser lakes close by. Mean rates of groundwater flow were greater than 2600 meters per day, indicating that there is a system of large and well integrated caves channels under the accessible karst. The White Spray springs flow all year round, rising from the river bed and keeping it locally ice-free throughout the winter. The mean discharge must be in excess of several cubic metres per second but is difficult to gauge as most of it enters below the River's surface and quickly mixes with the other water there. The "Spray" itself is the summer overflow, gauged at ~5 cubic meters per second on one day in July 2006.

The Bubbling Springs emerge along 500 metres of low cliffs at the top of the limestone, where it dips under shales in the Sundog Syncline, the valley between Tower Anticline (TA), and the Ram Plateau. Work in the 1970s established that the northern sector of the exposed karst, plus karst buried by glacial deposits (the Suffosion Sinkhole plain (SS), west of the springs), drains to these springs. In very wet conditions in 2007, their discharge was estimated at more than 10 cubic metres per second.

The Nahanni karst landforms are at their best in the remarkable Labyrinth, a mixture of corridors up to several km in length that are interspersed with broader, squared depressions. There are many shaft and funnel sinkholes on the little limestone plateaus and benches between the corridors. On higher limestone slopes to the west the corridor karst is replaced by more muted limestone pavement. There is no pavement landform
development on the Nahanni dolomites, in contrast to the situation in the northern Mackenzies.

In Area #2, Tower Anticline (TA) is a dissected dome where the limestone rests on the weaker Headless and Funeral dolomites and shales. Canyons have worked their way headwards to undermine the limestone plateau and destroy most of what must have been a magnificent pavement and sinkhole karst. Only a few scattered relicts remain at the surface. Tower Syncline (a striking downfold alongside the anticline) is better preserved and has many tributary canyons with attractive pinnacle topography, but little karst because the covering shales were stripped off the limestone more recently, when permafrost became established and was able to limit groundwater flow.

Area #3 is the “Castellated Karst”, an outstanding grouping of limestone tors displaying karst pavement and periglacial (frost sorting) features. A couple of the examples look like giant Stone Age fortresses of Europe. Further west the Prairie Creek Pavements (Area #4) are developed on Nahanni limestone dipping northwards at 10^{o}. They are extensive and well formed but are now degraded by frost shatter.

Area #5 is the western flank of Ram Plateau, the best preserved dome (anticline) known to the author in the Mackenzie Mountains. Streams in the two canyons at the southwest corner sink underground and drain to Bubbling Springs. Two newly discovered springs of unknown source burst from cliffs to the north. The former course of Ram River, through a broad canyon north, was plugged by glacial lake sediments, diverting the river into Scimitar Canyon (SC) a young, narrow, and vertically walled entrenchment that is truly spectacular.

The principal relict (i.e. drained and abandoned) river caves of enterable size are found in the north wall of First Canyon and its tributary, Lafferty Canyon. They were formed at or just below the level of the River but are now raised 280 metres to 600 metres above it by the anticlinal up-doming processes. Grotte Valerie and Grotte Mickey are the largest and most complex, each with more than 1000 metres of mapped passages. They contain some small but attractive modern (i.e. actively growing) stalactites and stalagmites, and many much larger and more ornate stalagmites and columns known to have grown in a warm interglacial period more than 400,000 years ago. Much of the earliest work on dating ancient speleothems that is now a key element in understanding continental climate change during the past one million years was done by the author’s McMaster research group utilizing samples collected from these caves. There are also attractive displays of seasonal and perennial cave ice and the skeletal remains of many Dall’s sheep, some with fragments of flesh and skin preserved where ice quickly covered the corpse to protect it from the attentions of bushy-tailed wood rats.

There are further caves in the Labyrinth and around Death Lake but most quickly become blocked by ground ice or frozen silts from a proglacial lake. New groups of relict stream caves were discovered in 2006 in the valleys at the east end of Tower Anticline and are now being explored under Parks Canada guidance. The greatest yet mapped is 900 metres in length but in other dimensions smaller than the caves of First Canyon.

Further west in South Nahanni Park and the expansion area, there are occasional small sinkholes, patches of pavement, and a few small springs but they are not judged to be significant. However, Rabbitkettle Hotsprings (at 61^{o} 55’ N and 127^{o} 15’ W within the existing Park) are certainly significant. They are magnificent examples of <u>constructive</u> karst landforms, structures built up by progressive deposition around the orifice as hot water, which has dissolved limestone at depths of more than one kilometre, reach the surface and discharge excess carbon dioxide (CO_2) in the lower pressure environment. They precipitate the limestone again as pure calcite ($CaCO_3$). The limestone is present at depth on the east flank of a major plutonic mass in the Ragged Range. One example is North Mound, a structure some 50 metres in height and even larger in width, which, from the air, resembles a giant wedding cake. Water emerges at a temperature of around 22^{o} C year round. South Mound, nearby, is a smaller, less distinctive spread on glacial terrace deposits. Rabbitkettle Hotsprings are the largest karstic hotsprings deposits reported in Canada.

3.3.2.3. Sheet 95G – Sibbeston Lake

Areas #1 and 2 and environs are the larger part of the Ram Plateau, which is bisected north-south by the map sheet division at 124° W. From its southern extremities, to the surface drainage divide north of the Ram River canyon that crosses it, the Plateau is included in the expansion of Nahanni National Park Reserve. South of Ram Canyon, the Plateau is capped by the Nahanni limestone resting on the resistant Arnica and Manetoe dolomites, as is the case at First Canyon. It rises to elevations of 1500 metres and is dissected by a series of magnificent, steep-walled tributary canyons. Between them the Plateau offers wonderful hill walking with extensive views. Like Tower Syncline, it is believed that Ram Plateau was uplifted quite recently, after in-growth of permafrost had begun in the region (Ford 1991). As a consequence karst development is more limited than around First Canyon or Tower Anticline. There are a few patches of limestone pavement and small shaft sinkholes around Area #1, which is the highest part of the Plateau and the first to rise. Area #2 is a small but distinctive patch of Nahanni Labyrinth-type terrain with corridors and several vertically walled sinkholes, one of which has a cave halfway up the wall. There two small natural bridges.

Note 3 (Area #3) draws attention to the Yohin Lake Pseudokarst. Pseudokarst is the term used to describe karst-like landforms created by processes other than bedrock dissolution. Thermokarst, creation of collapse sinkholes by the melt of ground ice masses in unconsolidated rocks, is a type common in arctic Canada. Volcanokarst is found in most volcanic terrains. The Yohin Lake features are a third type – piping pseudokarst. The unconsolidated glacial deposits, between the lake and the South Nahanni River, have layers of large coarse gravels that are overlain by proglacial lake silts. Water from the River has spilled through the large pore spaces between the gravel particles, washing out temporary caves into which the fine-grained silt particles are washed like sand being sapped through the bottom of an opened hopper. This produces large collapse and suffosion (funneling) sinkholes that are up to 200 metres long at this site. The north edge of the lake itself is the cliff remaining from the edge of an eroded sink. The Yohin Lake Pseudokarst is amongst the finest I have seen in Canada (Nahanni Reserve Description and Analysis 1984, pp. 4-104-6).

3.3.2.4. Sheet 95J – Camsell Bend

This sheet includes both the northeastern extremities of the southern Mackenzie Mountains Karst Survey Region and the southern end of the McConnell Range Region as defined in this Report. This description, however, is limited only to the southern Mackenzies portions.

Area #5 is the Camsell Range that is a typical narrow, steep dipping front range. The Nahanni Limestone is prominent along the crest but, as in other steep dip situations, karst is very limited. A few scattered sinkholes were noted where the crest broadens.

East of Battlement Creek at the northeast end of the Ram Plateau there is shallow, ice-modified corridor karst and a few large but shallow sinkholes on west-dipping slopes of Nahanni Limestone. The author

visited the area one afternoon in 2007 and has photographs. It is not judged to be a very significant karst locality.
The lower course of Battlement Creek is of considerable geomorphic interest. It first entrenched a broad canyon with an asymmetric cross-section, gently sloping on the eastern side and steeper on the west due to the westward stratal dip. Into this feature a narrow, slot-like lower gorge with vertical walls has been created by the recession of a waterfall, as at Niagara Falls and Gorge. It is a 'textbook' example of polycyclic landform development.

3.3.2.5. Sheets 95K – Root River, 95M – Wrigley Lake and 95N – Dahadinni River

The structural geology of Sheets 95K and 95N are dominated by tight folding and overthrusting in the same Paleozoic rocks as are found in the Nahanni region to the south. Sheet 95M lies largely to the west in the Backbone (igneous rock) Ranges but has Paleozoic strata along the eastern edge that continue the northwest trend of the Canyon Ranges.

The Nahanni Limestone outcrops quite frequently, but chiefly on narrow ridge crests or flanks. Stratal dips are generally very steep. Narrow outcrop and steep dip tend to limit or prohibit good karst development. One broader outcrop of the Limestone around 62^{o} 45' N, 125^{o} 45' W in the Painted Mountains could not be viewed adequately due to poor photo quality yet it may have some significant karst occurrences.

The principal karst features discovered by the air photo analysis are found widely scattered along the Iverson Range that forms the eastern (or front) range of the Mackenzie Mountains. The North Nahanni River has carved a short but attractive canyon across the southern end of the Range; personal correspondents have mentioned sightings of possible caves in the canyon walls but there are no details. The northern extremities of the Nahanni Plateau also extend into the southern part of the sheet. There are a few small and scattered sinkholes but no major features were detected on the air photos.

Area #1 is the northern Iverson Range. This Range extends onto the southern edge of the Dahadinni sheet but its first karst is seen on Kaytay Mountain on the Root River sheet. The summit exhibits a rugged karst of small corridors or bogaz and possible pavement in the Nahanni Limestone. There are two large funnel-type sinkholes and one prominent vertical shaft. The topography is also castellated. This site merits a field visit.

Area #2 on Sheet 95K has some rugged bogaz karst and small sinkholes. It is similar to Area #1 but probably less significant.

"Horseshoe Lake Glaciokarst Depression" (author's unofficial name). This is an amazing feature. Two small glacial cirques (typical alpine landforms) are carved into the limestones and (chiefly) dolomites of the Arnica and Funeral Formations that are beneath the Nahanni Limestone. Both are 'over-deepened', meaning that glacier rotational sliding action has carved the floors below the level of the outlet so that there is a bedrock sill enclosing a topographic depression. Over-deepened cirques are common in strong rocks of all alpine regions but if not in karst rocks they will fill with water to the sill level (forming a 'tarn') and spill across the sill in a regular surface stream channel. In the Canadian Rockies, the author mapped more than 100 over-deepened cirques in limestone where either there is no tarn (the water drains out karstically through the bottom of the cirque), or the water line is below the level of the sill and drainage is into a cave.

At “Horseshoe Lake” the two cirques have partly amalgamated by eroding away their party wall. This has merged the two over-deepenings to create one, horseshoe-shaped, closed depression behind the bedrock sill. The lake in it is below the sill level, i.e. it appears that it must be draining into a karst cave of some size. The 1:50,000 topographic maps do not record a closed depression here but, unfortunately, the junction of two topographic sheets passes through the southern (lakeside) flank of the sill, so this may well be a cartographer’s error. In the photos, the sill appears to be in bedrock and this was confirmed by an independent inspection by another air photo specialist present in the National Air Photo Library at the time. It is estimated to be more than 20 metres in depth to the waterline. *In the author’s experience, this landform is unique and certainly merits further study.*

3.4. McConnell Range of the Franklin Mountains

3.4.1. General Description of the Region

From the perspective of karst features within the Northwest Territories, the McConnell Range of the Franklin Mountains includes the 1:250,000 topographic map sheets covering the McConnell Range are: 95J- Camsell Bend, 95O – Wrigley, 96B – Blackwater Lake, and 96C – Fort Norman. A map showing the karst features in the McConnell Range of the Franklin Mountains Region can be seen in Appendix B.

The Franklin Mountains are series of thrust and fold ranges east of the Mackenzie River. They are not as numerous, large or complex as the Mackenzie Mountains because they are further from the injected plutonic rocks that provided the source of the energy. Nevertheless, they are substantial and prominent. An important feature of their geomorphic history is that they have been overridden and buried several times by the Laurentide Continental Icesheet. As a consequence, they display the effects of glacial scour and other effects much more strongly than most ranges in the Mackenzie Mountains.

There is a large gap in the continuity of the Franklin Mountains at the junction of Great Bear River with the Mackenzie River. The McConnell Range lies to the south and is considered here. The Norman Range and many lesser ranges are to the north and are considered within the Norman ranges and Plateaus region discussed in Section 3.5.

The significant karst rocks in this region and all later regions in this Report are chiefly the northern Paleozoic suite described in the Ford (2008), pages 29-34. At the base are the Mount Cap Formation of sandstone and siltstone and the Saline River Formation of redbeds, yellow siltstones, and dolomites with gypsum and salt units interbedded. Overlying them are the regularly bedded, mechanically strong, dolomites of the Franklin Mountain and Mount Kindle (or Tsetso) formations that are the foundation rocks of the northern ranges and host much of the modern karst. Each has a maximum 400 metres thickness. There was a long erosional interval between the deposition of these two formations, which is marked by paleokarst features in some places. The Mount Kindle is succeeded by the Bear Rock Formation, the very remarkable dolomite-gypsum solution breccia that is key to most other karst development in northern Northwest Territories. It is overlain by the Landry and Hume Formations, limestones ~100 metres in thickness that are succeeded in turn by the shales and shaly limestones of the Hare Indian Formation which is not karstic. Above the latter are the Ramparts and Key Scarp limestones, also less pure and not known to have significant karst. Following this deposition, the Paleozoic rocks were then subject to a lengthy period of erosion before being buried by shales, siltstones, and sandstones of Cretaceous age that still partly or entirely cover them over much of the plateau and plains country. In the southern parts of the Range, the Nahanni limestone and the overlying Fort Simpson shale replace the upper limestones and shales.

The McConnell Range has a large variety of karst features and merits much closer study.

Site description begins in the north at Fort Norman. It was the first part of the McConnell Range to be studied on the air photos because it is closest to the Norman Range that was already well known from field study in 2007.

3.4.2. Specific Description of Features and Areas

3.4.2.1. Sheet 96C - Fort Norman

Areas #1 and #2 are small outlying highlands in the Franklin Mountain dolomite and some younger strata. The geologic structure is locally complicated by block faulting within the general overthrust architecture. There is angular but subdued karst corridor topography plus small depressions swallowing flowing streams in Area #1. Area #2 is strongly lineated due to the steep dip of the dolomites and has a few apparent small sinkholes within linear (strike-oriented) troughs.

Area #3 is Mount Clark, for which the geologic formation is named. Here it is strikingly white, mechanically strong, quartzitic sandstone. Even on small scale air photos it appears to display some classical sandstone weathering features, so it can be expected to have typical small karst forms such solution pits, pans, and grikes, as described in Ford & Williams (2007, pages 388-91) from the high plateaus of northern Brazil and southern Venezuela. It will be interesting to compare the two regions, glaciated versus unglaciated, and a field visit is recommended.

Area #4 is a mélange of Franklin Mountain, Mount Cap, and Saline River rocks that appear to have foundered due to interstratal dissolution of salt and gypsum. There is one significant closed depression and some lesser sinkholes. This site is complex and merits a field visit.

Bear Rock (Area #6 - the southern extremity of the Norman Range) is proposed for a cultural protected site (Sahtu Heritage Places, 1999). It is developed in Bear Rock and Hume strata plus the underlying dolomites. There is a very rich and striking display of karst landforms including a major depression hosting two permanent lakes, many lesser closed depressions, sinkholes, pinnacle ridges (the best seen anywhere on Bear Rock Formation strata), and major springs with big icings. Full details are given in Hamilton (1995, pages 398-441) and Ford (2008, pages 59-69).

West of the Mackenzie River, the Mackay Range (Area # 5) is nearly fully karstic in drainage. Like Bear Rock it is developed chiefly in Bear Rock and Hume strata. There is a large central closed depression following a thrust fault, with lesser but sharply defined sinkholes on the flanking ridges. Groundwater drainage is to small springs around the perimeter. Those on the east side have water chemical concentrations typical of flow through the Bear Rock breccia. West side springs are presumed by the presence of lakes but have not been studied. The ridges show muted pinnacle and ice scour forms, similar to Bear Rock itself but less significant. There are excellent periglacial landforms, including at least one rock glacier. Details are given in Hamilton (1995) and Ford (2008, pages 123-130).

3.4.2.2. Sheet 96B – Blackwater Lake

This sheet contains a narrow sector of the McConnell Range east on the Fort Norman sheet. The geology is quite complex, with much faulting as well as overthrusting. Although dominated by the karst rocks, there appears to be little karst in the easternmost range due to steep stratal dips and narrow ridges that limit catchment for groundwater.

Area #1 is the Pedaytayshe Mountain on the Bear Rock breccia. The summit area is a sloping plateau at and just above tree line with abundant small pond sinkholes and a few of the characteristic Bear Rock pinnacles. There are also some sinks in the underlying dolomite.

Area #2 is of narrower plateaus and west flank benches on the Landry and Hume limestones with similar small pond sinks and a few dry sinkholes.

3.4.2.3. Sheet 95O – Wrigley

This sheet covers the central and broadest portion of the McConnell Range. Due to the organization of the air photo flight lines, it was studied from south to north and is reported here in that sequence. There is karst development throughout its extent. Given the small scale of the photos and the limited time available, it is certain that more detailed studies with larger scale photos (where available) and in the field will discover much more.

Area #1 contains a number of small probable sinkholes. A larger stream flows in from the east and sinks underground. The area is mapped as Fort Simpson shale but there is a shallow overthrust on the Nahanni limestone and Bear Rock breccia, so the karst is probably draining into one of these units.

In Area #2 there are small patches of solutional pavement on Nahanni limestone slabs and a closed depression, in a glacially widened valley, cut through them.

Areas #3, 5, 7, and similar locales in between them are all mapped as Quaternary alluvium (river terrace) deposits on top of Fort Simpson shale. They have distinct clusters of circular ponds that suggest a possible suffosional collapse origin into underlying limestone. In many of these locales, larger closed depressions around them have water levels that appear to fluctuate quite substantially, which is additional evidence. In the Nahanni karst, it is established that suffosion is occurring through as much as 50 metres of cover shales and glacial terrace deposits over the limestone. Alternatively, there may be pseudokarst piping occurring here as it does at Yohin Lake in the Nahanni region.

In Area #4 a substantial lake on the Fort Simpson shale, plus streams flowing from the range to the east, sink into the exposed edge of the Nahanni limestone or, possibly, the Bear Rock breccia that is emplaced beneath by overthrusting.

On Smith Ridge and Bell Ridge, there are some glacially modified pond sinkholes in the Nahanni limestone, the Bear Rock breccia, and, possibly, the underlying Mt Kindle dolomite. They are widely scattered but there may be many smaller examples in between.

At Area #8 there is some Bear Rock pinnacle topography in close juxtaposition with the Nahanni limestone. To the east, Cap Mountain is built of older Proterozoic carbonate and other strata and does not display karst features. On Mount Kindle, the dolomites named for it are well exposed but dipping steeply; there appears to be little or no karst development except, possibly, at scales too small to be seen on the air photos.

There is a prominent Nahanni limestone pavement at Area #9 that is surrounded by Bear Rock breccia. There is probably substantial karst drainage here via many small sinks in the breccia, northwards to the south side of the Ochre River valley.

The McConnell Range between Ochre River and Blackwater River is chiefly in the Franklin Mountain, Mt Kindle, Bear Rock, and Nahanni formations. Although often steeply dipping and much dissected, there appears to be a wide range of karst landforms present. It is perhaps the core area of McConnell Range karst. In Areas #10 and 11 there are many patches of high pavement on the Franklin Mountain and Mt Kindle dolomites, plus small sinkholes in them and in the Breccia.

In Area #13, there are pavements on the Nahanni limestone, small scattered sinkholes, and some dry valleys on the Breccia. Site #13A is a very fresh sinkhole in the 1973 air photos. It is big (>100 m in diameter) and deep, and without a pond in it. The outline is very sharp.

In Area #14, Nahanni limestone and the Breccia are again juxtaposed. There are sinkholes on both and a large closed depression in the Breccia takes a sinking stream.

In Area #15, there are some small pinnacles on the Breccia.

3.4.2.4. Sheet 95J – Camsell Bend

This sheet contains the southern extremity of the McConnell Range. It is karstified to the very end.

In Areas #1 and #2, steep stratal dip prohibits the development of larger karst landforms. There are attractive chevrons on the more southerly ridge. A stream that drains it to the south, along the strike of the rocks, turns abruptly west and sinks, probably into the Breccia.
In Area #3, Willow Ridge is an anticline in the Nahanni limestone with the Breccia expose in the core. There are a few small sinkholes in the latter.

In Area #4, there are three quite large closed depressions and one large, fresh collapse sinkhole. The strata again are Nahanni limestone over Bear Rock breccia.

3.5. Northern Franklin Mountains, Low Plateaus and Hydration Ridges between Great Bear Lake, and the Mackenzie River

3.5.1. General Description of the Region

This very large geographical area includes karst landforms and groundwater systems on the 1:250,000 topographic sheets: 96E – Norman Wells, 96F – Mahony Lake, 96K – Lac des Bois, 96L – Lac Belot, 96M – Aubry Lake, 96N – Lac Maunoir, 106I – Fort Good Hope, and 106H – Sans Sault Rapids. A map showing the karst features in Northern Franklin Mountains can be seen in Appendix B.

The karst in parts of it have been studied previously by R.O van Everdingen (1981) and more is covered in Ford (2008), pages 36-119, but certain peripheral areas and one key central area have not been investigated in any detail. Taken together, the assemblage of plateau karst, hydration ridges, and overridden mountain karst must be considered to be one of the most significant – or the most significant - karst known in permafrost on the planet. Here it is considered in a sequence of the 1:250,000 sheets from the easterly and southerly low plateaus (Sheets 96F, 96K, and 96L), through the hydration ridges to the northern and westward limits (Sheets 96M, 96N, and 106I), and then concludes in the Ranges around Norman Wells that have been comprehensively overridden and modified by flowing Laurentide ice (Sheet 96E).

In the area where karst sinkholes, closed depressions, and springs were mapped at the 1:50,000 scale by van Everdingen (1981), his results are simplified and copied onto the 1:250,000 sheets here, with some additional interpretation. The remaining mapping is based on the 1:50,000 air photo analyses of September 2008.

The most significant karstic rocks in the region are the Franklin Mountain and Mt Kindle dolomites, and the Bear Rock breccia. The overlying limestones play only a minor role. There appears to be quite frequent karst collapse through thin covers of the Cretaceous strata in some areas as well.

Three key low plateau karsts may be defined: the Mahony Dome,the Tunago Dome, both of van Everdingen (1981), and the Lac Belot Dissected Plateau, that is briefly mentioned in Ford (2008), pages 113-119. The two domes are located south and north of the eastern half of the Hare Indian River valley, respectively. Part of their karst drainage is directed into the dome and part is dispersed to other springs (mostly unrecognized) elsewhere around their perimeters. The Lac Belot Dissected Plateau drains underground to a major north bank tributary of the Hare Indian River that has incised a valley into it further west.

3.5.2. Specific Description of Features and Areas

3.5.2.1. Sheet 96F – Mahony Lake

Karst features here are simplified from van Everdingen's mapping (1981).

The Area of Note #1 is the ‘Mahony Dome’ itself. It is the finest example known to the author of a plateau with very gentle relief, dolomite (Franklin Mountain) rather than the more soluble limestones or breccia, and theoretically continuous permafrost that is still able to develop karst drainage. It displays a partial pattern of radial underground drainage outwards from its core but this is distorted by the steeper hydraulic gradients into the deeply entrenched Hare Indian Valley which is, most likely, able to capture more than its fair share of the catchment on the Dome. The centre is very flat and contains extensive muskeg. Ponds on it (for example, the Wright Lakes) and other streams all sink so prominently that their sinkpoints are even recorded on the 1:250,000 sheets. The catchments of some of the sinking streams are considerable, many of tens of square kilometres. Site #1B is van Everdingen’s closed depression #110. It is a fine example of turlough (seasonal lake) karst drainage in the Old Age stage of development in which a once continuous lake during the spring melt period is now reduced to smaller ponds captured by many separate sinkholes. It has previously been recommended for protection (Ford, 2008, pages 83-98). Site #1C is van Everdingen’s ‘Disappearing River’, a fine example of a river capture into a large, joint-guided sinkhole, with overflow sinks downstream. It is also recommended for protection (Ford, 2008, pages 99-102).

Note #2 covers an easterly outlying range of the Franklin Mountains and follows van Everdingen’s (1981) sinkhole mapping. The eastern Franklins are low in elevation and well treed; it is likely that many small sinkholes were missed by this mapping, so the sinkhole densities indicated here should be considered a minimum.

Note #3 refers to a large closed depression adjoining Yakeleyva Lake. It floods completely during the spring melt period and retains some large ponds throughout the summer. It is an excellent example of karst turlough development in the Youthful stage (Ford, 2008, pages 47-48).

Area #4 is part of the main ridge of the Norman Range, southeast of the community of Norman Wells. It is formed chiefly in the Franklin Mountain dolomites. It has been strongly ice-moulded by glaciers flowing from the east. It exhibits good examples of glaciokarst sinkholes and larger closed depressions on both the east (scarp) and west (dip) slopes (Ford, 2008, pages 36-46).

The topographic and groundwater hydraulic gradients are very gentle on the flanks of the higher karst uplands on this Sheet. It is very difficult to establish where the boundaries between predominantly underground drainage and surface run off occur in such circumstances. The boundaries indicated on the Sheet should be treated as broad generalizations only; they will not be accurate in detail.

3.5.2.2. Sheet 96K – Lac des Bois

This sheet covers Tunago Dome, the second key lowland element in the regional karst, and the lower karstic plains, extending further north to the shore of Lac des Bois. It includes most of Tunago Lake and its catchment. Franklin Mountain dolomites underlie the Dome but are replaced by Mt Kindle dolomites to the north. The area of Note #2 appears to have received deeper glacial scour than Mahony Dome and so has more irregular surface features. There are patches of corridor karst that are broad but shallow and substantially concealed by glacial deposits. Glacial drift is piled up deeper in places to the north. Where the corridors are not infilled, they often function as stream sink points or contain seasonal ponds. There are relatively few fresh shaft or funnel-shaped collapses and suffosion sinkholes. Because the terrain has very gentle gradients, most features are shallow and expose no bedrock. These include some very large closed depressions that have drainage basins tens of square kilometres in area. The full extent of sinks and whereabouts of springs is difficult to establish because of the low relief and glacial drift cover. It is most likely that van Everdingen and the author have significantly underestimated the number and patterns of karst sinks at this location. See the Ford (2008), pages 109-112 for illustrations.

The elongated closed depression shown at Note #3 is van Everdingen's Sinkhole #142. It is a turlough that obtains most of its drainage to the south of the Lac des Bois sheet. In the Ford (2008), pages 77-82, it is recommended for protection as an excellent example of a turlough in the mature karst drainage stage.

Note #4 focuses on springs in the Hare Indian Valley. Only those reported and mapped by van Everdingen or visited by the contractor in 2007 are shown because of the difficulties of detecting the smaller springs by air photos alone. The red star symbol on the map in Appendix B (labeled with on "I" on the paper maps, see Editor's Note for more detail) refers to an 'icing', a spring that discharges groundwater throughout the winter, building a large apron of ice at the outlet. The precise locations of the springs feeding the icings were not established.

In a personal communication with the author on November 20 2008, Mr Richard Popko, Wildlife Technician for the Government of the Northwest Territories, Norman Wells, stated that a Fort Good Hope trapper, Wilfred Jackson, mentioned that Tunago Lake dried up in the last few years and that the water all disappeared in an underground river to a tributary of the Hare Indian River. He was working with a seismic exploration company and it was too noisy from all the underground water to conduct their seismic survey.

Tunago Lake (Note #5) is marked as a permanent lake on all topographic maps and appears to be so in the Landsat and Google Earth images. The topographic maps show it draining at the surface, but only very tenuously via a channel that appears likely to be too small. The information stated above suggests that it is behaving in a similar manner to Lac Belot, sinking into an anhydrite hydration ridge, as described below in Section 3.5.2.3. The mention of underground flow disrupting seismic exploration is unique in such low relief terrains. Given that Tunago Lake has not been recognized as anything other than a permanent lake in previous topographic and geologic surveys, it is possible that the effective underground drainage described by Mr Jackson through Mr. Popko is a new development that may be related to partial melting of permafrost, which may be very rapidly evolving karst drainage. It certainly merits further field study.

Underground drainage boundaries on this Sheet are approximate, for the same reasons given above for the Mahony Lake sheet (Section 3.5.2.1). The topographic and groundwater hydraulic gradients are very gentle on the flanks of the higher karst uplands on this Sheet. It is very difficult to establish where the boundaries between predominantly underground drainage and surface run off occur in such circumstances. The boundaries indicated on the Sheet should be treated as broad generalizations only; they will not be accurate in detail.

3.5.2.3. Sheet 96L – Lac Belot

This sheet contains the third key element of the Great Bear karst plateau country, the Lac Belot karst. In topographic maps and photos, it is the most densely karsted of the trio. Van Everdingen did not map it, so the features depicted are based on the small scale 1:50,000 air photo and topographic map surveys alone. The area is geologically more complicated than on the two domes. The most important point is that the readily karsted Bear Rock Breccia is at the surface or under shallow cover over much of the sheet. In the southeast corner, the underlying Mt Kindle dolomite outcrops on the east side of Tunago Ridge, while the overlying Hume limestone outcrops on the other; this suggests that intense dissolution has removed most or all of the intervening breccia, except along the uplifted ridge itself. It stresses the intense karstification that may have occurred over much of the map.

The Hare Indian River Valley is entrenched across the centre of the sheet to serve as the regional outlet for karst groundwater and tributary surface streams. It will be seen that, along much of its course, the plateau flanks are capped by Hume limestone (purple line shading[1]), resting on the Breccia. The cap is evidently thin; small sinkholes and isolated lakes draining underground (almost certainly into the Breccia) are common and widely scattered. There are patches of ice-scoured limestone pavement on the Hume. Brown line shading[2] indicates that the Hare Indian shaly, non-karstic strata or overlying Cretaceous shales are concealing the karst rocks beneath a cover that thickens to the west. As a consequence, the frequency of sinkholes drops off rapidly, but the boundary of all karst drainage remains very uncertain.

Three major features exert strong control on the distribution of karst landforms on the Sheet: the hydration ridges, an unnamed north bank tributary of the Hare Indian River that has entrenched the Plateau and captured the drainage of Lac Belot underground, and some very strong east to west glacial lineation.

It has been proposed that Lac Belot Ridge and the sector of the Tunago Ridge on Sheet 96L may be the products of the hydration of anhydrite at shallow depth in the Bear Rock Formation (Cook and Aitken, 1973). Hydration can increase the volume up to 35%, creating gypsum and buckling overlying rocks (of any kind) upwards into blister-like bursts. The strong and continuous form of the ridges suggests that hydration may have taken place along temporarily stagnant Laurentide glacier ice fronts. Abundant meltwater will be present under pressure, under the ice and there can be rapid hydration that is narrowly confined by the impediment, especially if its outflow is impeded by permafrost growing into the recently vacated glacial forefront, as is suggested here. The Lac Belot and Tunago ridges are 50 to 150 metres in height and several kilometres wide (Ford, 2008, pages 113- 119).

The unnamed north bank tributary heads at the point marked Lac Belot Springs on the map, where it is entrenched approximately 100 metres below the general level of the enclosing plateau. It is where the Legend of Neyadalin map (Ford 2008, page 115) places springs and is the most likely point for them based on technical hydrogeological grounds. It is suspected that much of the valley downstream was produced by a process of spring headward sapping, a mechanism that creates *steepheads* (*reculées* in French), valleys retreating into plateaus that are reported in karst regions worldwide (Ford & Williams, 2007, p.365). Its exceptional length by world standards and makes it a very good example of this type of formation. This may be a consequence of the Breccia's high solubility. As it sapped headwards towards Lac Belot, the steephead was steepening groundwater hydraulic gradients on either flank as well. As a consequence, the greatest densities of sinkholes in the region are seen where the Breccia is exposed in the steepened hydraulic zones with a protective Hume limestone cap on top; many are fresh in appearance and it is evident that karst activity is very vigorous today. There is a particularly marked belt of high density

[1] Purple shading is on the paper maps only. See Editors Note for more details.
[2] Brown line shading is on the paper maps only. See Editors Note for more details.

extending along the west flank towards the putative sink point of Lac Belot. Note also that the topographically closed depressions in this area and north to Lac Belot are also of exceptional size.

There are several areas on Sheet 96L that display exceptionally strong glacial linear scouring, ice flow evidently being from east to west. The scour is greatest immediately west of Lac Belot Ridge and the southern sector of Tunago Ridge. Across the top of the Sheet (Note #1), it appears that scour carved a channel through the shaly cover rocks. Sinkholes are widely scattered along this channel, diminishing in frequency to the west. The effects are the same in the belt indicated by Notes #7 and #8, but the density and scale of the sinkholes are less. In some instances it is thought likely that the karst features are older than the glacial scour and have been modified by it.

The sinkpoint of Lac Belot marked on the map is based on a drawing accompanying the legend. It has not been confirmed by groundwater tracing but, as noted, is a likely connection. The straightline connection between the putative sink and spring points is ~20 kilometres and the fall height is ~75 metres, giving an average groundwater hydraulic gradient of around 4 metres per kilometre, which is quite sufficient for fast groundwater flow and cave development in such strata (Ford, 2008, page 119).

At Notes #18, 19, and 20 in green ink there are attractive limestone pavements on Hume limestone, with frequent small sinkholes close to the escarpment edges.

At Notes #22 and 23 in green ink the effects of adding Hare Indian Formation shale cover to the Hume cover on the Breccia is particularly well marked; there is a clear reduction in the frequency and size of sinkholes, but a few still break through.

At Notes #31 and 32 in green ink there is a cluster of sinkholes where the tributary valley turns sharply; the turn is probably guided by a fracture trend that has favoured more groundwater flow.

The number and variety of karst features on the Lac Belot sheet is very rich. One can understand why van Everdingen chose to avoid it in his pioneer investigations of karst development in the region! Time did not permit the author to make a truly adequate review of the karst here. It certainly warrants further, more detailed study.

3.5.2.4. Sheet 106I - Fort Good Hope

The Fort Good Hope sheet is summarized next in the Low Plateau sequence because it lies west of the Lac Belot sheet and thus is downstream along the glacial scour trends that are important karst locators on the latter.

It appears that there is very little outcrop of the Bear Rock Breccia on the map sheet and that the Hume limestone is generally covered by Hare Indian shales and upper, rather impure, limestones (Ramparts and Key Scarp). On the Ramparts Plateau west of Loon Lake and Loon River, air photo survey along sample transects only suggests that there are quite a large number of sinkholes and lakes likely to be draining underground but that they are widely scattered and have been subject to glacial modification in many instances (possibly partial infilling and obstruction). The Plateau merits further study but it is not thought likely to have karst of the significance of that of Lac Belot and other sheets to the east.

The strong association between glacial lineation and sinkhole location, as noted in Section 3.5.2.3. on the Lac Belot sheet, continues westwards along the flanks of the Tchaneta River on this sheet and there is an especially high density southeast of the junction with the Bluefish River. The karst-lineation trend line of Note #7 on the Lac Belot sheet continues southwestwards towards Lake Ontadek and Fort Good Hope but with a lower frequency of sinkholes. There are further groupings of possible sinkholes (possibly glacially modified and partly infilled) at quite high frequency east of Loon River and immediately north of Loon Lake.

Time did not permit a thorough review of the karst potential on the Fort Good Hope sheet. In general, it does not appear to be as significant as on the sheets further east.
However, the author has received several reports of interesting karst or pseudo-karst features in the area of Note #1, on the west bank of the Mackenzie River. This area was missed in the air photo traversing in September 2008. Some helicopter photos supplied by Mr David Downing, taken in the mid 2000s, show what appear to be very fresh and evolving suffosion sinkholes in river or glaciolacustrine unconsolidated sediments close to the River. One 800 metre shallow closed depression with a permanent lake is plotted on the 1:50,000 topographic map further to the west. It is concluded that there is modern karst activity in the area but the karst rocks involved and the depth of unconsolidated cover sediments on top of them is not known.

3.5.2.5. Sheet 96M - Aubry Lake

This map sheet covers the land immediately north of the Lac Belot and was studied carefully to track the northerly limits of karst development. These proved to be difficult to establish, at least working with the 1:50,000 scale air photos.

The southerly terrain between Lake Tadek and Belot Ridge is mapped as having Cretaceous shale cover but it is curiously hilly and irregularly dissected, not typical of landform patterns on the shales elsewhere. It is thought there may have been an abundance of small karst collapses through the shales that are now partly infilled. The regional water-table is high here (essentially at the surface in all low spots), so that any true collapse sinks are flooded, and will be overflowing during the melt season at least.

The northern end of Belot Ridge is sharper and narrower than it is to the south on the Lac Belot sheet. There are no open ruptures or obvious sinkholes as there are further south, suggesting a less evolved expansion. Bedzia Mountain and the unnamed height along the ridge to the south are broader and more broken features, however, suggesting vigorous hydration and uplift beneath them.

The bedrock geology in the area around Note #3 is very poorly known due to a lack of outcrops. Some Hume limestone has been reported to the west of it and Bear Rock breccia to the east. All of the larger lakes shown here may be of glacial scour origin or may be older glaciokarst. Many of the smaller ponds around them are simple circular features suggesting collapse into the Breccia. The general topography here is reminiscent
of that around the ‘blueholes’ on some Bahamian islands that have been caused by the post-glacial rise of sea level. On Aubry Lake an old karst may have been drowned by the rise of water level as a result of deposition of glacial debris.

3.5.2.6. Sheet 96N – Lac Maunoir

This sheet covers terrain east of Aubry Lake and north of Lac des Bois. The western portions are known to have Bear Rock breccia at or close to the surface but, as in the adjoining Aubry Lake country, there are few outcrops plus thick covers of most likely, glacial deposits mask possible karst activity. The area is low lying and swampy. Around Note #4 there is a cluster of small sinkholes with some small pinnacles of the Bear Rock type to the east of them. There may be similar groupings further north but time permitted only one sample air photo traverse across the top of the sheet, where a few small sinkholes and one sinking stream were detected.

Maunoir Ridge is a considerable feature, being up to 300 metres in height and ten kilometres in width. It is not established whether it is a simple product of hydration (a very big one) or it is a displacement thrust augmented by hydration. In the south (Note #2), Maunoir Ridge is similar to Belot Ridge in form, though larger. There are substantial sinking streams and closed depressions holding small lakes on either flank that are aligned along the axis of the uplift and represent bursting ruptures. They are up to 30 metres in depth. There are many lesser, irregularly shaped (not oriented) sinkholes created by rupture at intervals along the crest of the Ridge. Colville Ridge to the west is also similar in form but more muted. There a few small sinkholes.

Maunoir Dome is the strongest topographic feature, with 300 metres of local relief. It is reminiscent of the form of a simple salt dome or diapir and thus may be the product of plastic flow in Saline River salt or gypsum from the Saline River or Bear Rock strata. The exposed surface appears to be in dolomites. Franklin Mountain and Mt Kindle dolomites are mapped in the headwaters of the Anderson River to the east. The top of the dome is broken into corridor topography somewhat reminiscent of Nahanni. Here it is probably due to uplift rupture augmented by glacial scour, rather than karst dissolution.

The plateau around Note #1 in the southeast corner of the map is on Ronning Group dolomites (Franklin Mountain and/or Mt Kindle – undivided). It is quite rugged, hummocky terrain with prominent ice-rounded bedrock outcrops. There are two substantial closed depressions (more than3 kilometres in length) that swallow local streams and two small lakes apparently draining underground. Lesser depressions that are probably ice-modified sinkholes were also noted. The area here is quite like the karst around Bonne Bay Big Pond, Newfoundland (Karolyi and Ford, 1983), where a mature karst drainage system with major sinkholes was severely disrupted by morainic infilling during the last glaciation.

3.5.2.7. Sheets 96E – Norman Wells and 106H – Sans Sault Rapids

The karst features east of the Mackenzie River depicted on Sheet 96E are largely those mapped by van Everdingen (1981), generalised and with some additions. Much of this area is reported and illustrated in Ford (2008, pages 36-68) but the northwestern sector between Brokenoff Mountain and Gibson Ridge was not considered.

The area of Note #1 around Doctor Lake is the western, downslope third, of the Mahony Dome. The relief is low but karst is well developed in Franklin Mountain dolomites, including some substantial closed depressions (turloughs) that have not been investigated in any detail. The plateau west of Medzih Lake has small sinkholes and a sinking stream. The southern end of Tunago Ridge displays the rupture-type of closed depression found on Belot Ridge. The Jacques Range is narrow-crested but has sinkholes on the broader slopes on the west flanks. Van Everdingen mapped an important series of karst springs discharging into Kelly Lake and Lennie Lake.

The Norman Range on this sheet is a west-dipping multiple scarp terrain developed chiefly in the Franklin Mountain dolomite but with Bear Rock Breccia and formations up to the Key Scarp outcropping on the lower dip slope. Ice scour and glacial enlargement of prior karst depressions (glaciokarst) dominate on the upper slopes and crest, being a model for the impacts of overriding continental ice. There are many small scour depressions that drain underground; see Ford (2008), pages 36-46 for illustrations.

Note #3 identifies the quite famous Vermillion Creek Sinkhole, which is the finest example of a large, but simple, cylindrical karst collapse sink known to the author anywhere in North America. It is recommended for protection; see Ford (2008) pages 54-55.

The northern ridges of the Norman Range, Mount Richard, and northwards to Mt Effie expose steeply dipping lower dolomites, the Breccia, and overlying limestones and shales. The morphology is typically glaciokarstic. The line of six large closed depressions north of Mount Richard are in the Breccia; they have not been studied on the ground.

The northern Franklin Mountains extend across Sheet 106 H and terminates at the Sans Sault Rapids on the Mackenzie River. They are narrow thrust and fold structures like those immediately to the east on Sheet 96E. Site #4 on Sheet 106H, East Mountain, is a narrow breached ridge containing one substantial lake and several lesser closed depressions draining underground. Site #5, the Gibson Ridge, appears to be quite intensely karstified, with glaciokarst, recent sinkholes, and one larger closed depression. To the west and north there is further karst, chiefly sinkholes, in the Bat Hills and on Beavertail Mountain.

3.6. Northern Extremities: the Horton and Anderson River plateaus, the Campbell Uplift, and the Parry Peninsula

3.6.1. General Description of the Region

The Horton and Anderson plateaus and plains are covered on 1:250,000 topographic maps Sheets 96O – Horton Lake, 96P Bloody River, 97A Erly Lake, and 97B Simpson Lake to the north and west of them. The Franklin Peninsula is covered on Sheet 97C - Franklin Bay. A map showing the karst features in the Northern Extremities can be seen in Appendix B.

Much further west at the community of Inuvik, McGuinness (1999) has reported on a small area of corridor and sinkhole karst in Paleozoic limestones and dolomites of the Campbell Uplift. Although interesting and accessible, it is close to the airfield at Inuvik, because it appears to be a very isolated instance of karst development; it was decided not to carry the general survey for karst features this far to the west. Some icings reported in the Richardson Mountains on the Yukon border are similarly neglected

(Clark and Lauriol 1997). Their existence implies that there may be some karst groundwater circulation in the Mountains but the author is not aware of any other reports of karst landforms there.

3.6.2. Specific Description of Features and Areas

3.6.2.1. Sheets 96O - Horton Lake and 97A - Erly Lake

These two sheets are considered together because they share a belt of sinking stream karst along the Horton River that flows to the northwest. The sheets straddle the taiga-tundra boundary. The topography is of rugged, ice-scoured, plateaus into which the River has progressively entrenched a valley with a narrow flood plain to a depth of between 60 and140 metres. There are glacial deposits of varying depth over most of the area but most notably in the southwest quarter of the Horton lake sheet. There is a prominent chain of eskers trending north to northwest west of Horton Lake itself and extending to Estabrook Lake in the northwest corner of the sheet.

The bedrock geology is mapped as Ronning Group dolomites. They are the northeastern equivalents of the Franklin Mountain dolomites of the Mahony Dome, being very regularly bedded and nearly flatlying with little deformation by folding. The lower portion is described as pure, becoming more cherty and sandy (i.e. less soluble and more mechanically resistant) towards the top, to form a strong cap on the uplands. Early geological reports describe the lower unit as being anhydritic in part, which may explain the surprising extent of modern karst activity. Alternatively, it is possible that the Saline River salt and gypsum are close to the surface, especially in the esker chain on the Horton sheet. However, there are no characteristic big collapse sinks, so it is judged more likely that the development is in dolomites alone, perhaps rendered more soluble by thin beds and stringers of anhydrite.

The region should have continuous permafrost to depths of at least 50 metres, except beneath larger lakes and rivers.

Parallel to the River valley (area of Note #1 on both sheets), there is a belt of sinking streams that drains to springs in the Horton valley or lower sections of its more deeply incised tributaries. It must be emphasized that in these cold conditions the streams are able to maintain open (talik) channels through the presumed permafrost. There are sink points up to ten kilometres distant from the trunk valley floor, yielding hydraulic gradients in the range of 5 to 15 metres per kilometre to sustain flow through the frozen ground. Based on the geological mapping, it appears that most of the sinking is taking place into the lower, possibly anhydritic dolomite. More than fifty sinking streams have been detected on the air photos and 1:50,000 topographic maps, and there will certainly be smaller ones that have not been detected. A small proportion of the sinks are into shallow closed depressions up to one kilometre or so in length but most appear to pass into very shallow sinks or into the channel bed.

The ridges display locally rugged topography. There are occasional patches of dolomite pavement that appear to have suffered much frost shattering, however it is difficult to be sure with small scale air photos. More significant are patches of shallow and discontinuous bogaz, solution corridors now partly filled by glacial sediments. These may be sub-glacial/scablands channels or (more likely) ice-modified earlier karst or glaciokarst. There are a few small and widely scattered sinkholes on the plateaus, but as they do not retain water it must be assumed that they are able to drain karstically.

The Horton River stream sink karst is very substantial in extent and must be discharging large quantities of water during the hydrologic year. It is judged unlikely that it can have developed entirely under the conditions that have prevailed throughout most of post-glacial time in this region. It is more likely that there is a long history of karst and glacial interaction, and that inheritance from earlier conditions plays a significant role in maintaining the modern karst activities.

In Area #2 on the Horton Lake sheet, there is a chain of eskers with other glacial deposits that has a high density of small closed depressions in sections along it. It is uncertain how many of the depressions may be karstic rather than glacial in origin. If they are karstic, they appear to be suffosional (funnels in the glacial drift). However, there are some sinking streams within the chain, indicating that there is at least some local underground drainage into the bedrock occurring here.

These karst formations are a very striking example of fluviokarst development (or maintenance) in periglacial conditions and the best the author is aware of at high latitudes. They warrant further study.

3.6.2.2. Sheet 97B – Simpson Lake

Like the Erly Lake sheet, the Simpson Lake sheet straddles the taiga-tundra boundary. The Horton River, in its northeastern taiga quarter, is largely on the Ronning dolomites but its entrenchment is shallower and the cover of glacial sediments is deeper than on the Erly Lake sheet further upstream. No karst features are reported by the geological surveyors (Yorath, Balkwill, and Klassen, 1968) and none were found during sample air photo traverses under the present contract.

Over most of the taiga region to the south and west the surface bedrock is composed of shales and shaly limestones of the Hare Indian Formation or the younger Cretaceous clastic rocks. This prohibits karst development on the shallow plateaus.

Along the Anderson River, between Points #1 and #3 on the Sheet, the River channel has entrenched 50 metres or more below the shaly plateaus. The geological map (Yorath et al, op. cit) indicates that the entrenchment reaches down into the top of the Bear Rock Formation quite frequently, though not continuously. The geological report mentions that breccia pipes (rubble-filled cylinders created by cave collapse below) are occasionally exposed in the River valley walls. They appeared to be inert (permanently frozen) under modern conditions.

To investigate the course of the Anderson River, it was studied in some detail on the small scale air photos between Points #1 and #3, especially around Point #2 where the channel turns westwards and a broader exposure of the Breccia is suggested by the mapping. No obvious and fresh sinkholes, sinking streams, or drained closed depressions were detected. Along the plateau edges out to between 3 and 4 kilometres from the valley walls, however, there are occasional clusters of small circular ponds occupying what may have originated as collapse sinks. Many appear to be karstically inert today, i.e. they are draining by channels flowing out on the surface, but in other clusters there is evidence that water level fluctuated substantially. Some clusters were drained while neighbouring channels nearby retained a partial fill of water, but not enough to be discharging at the surface when the photos were taken. This suggests that there is limited karst drainage in a few small areas today.

The lack of significant karst development where the Breccia is reported to be present along the Anderson channel is surprising, given that a substantial and significant karst is found at the same latitude in the less soluble dolomites on the Horton River. The Anderson valley entrenchment is lesser and probably younger, which hints that the Horton karst may be quite old, originating before deep permafrost was established there.

3.6.2.3. Sheet 97C – Franklin Bay

The Parry Peninsula displays stratiform, ice-scoured surfaces on Ronning Group dolomites. It is singled out in this Report as the most striking example of comprehensively scoured carbonate rock terrain seen in this air photo survey of karst in the Northwest Territories. The relief is quite rugged at the local scale although the regional high points are only between 50 and 80 metres above sea level. Scouring has delicately emphasized differences in the resistance of successive beds of dolomite, so that forms vary. There are some small, ice-modified bogaz and shallow closed depressions that occasionally overflow, implying that there is little or no underground drainage today. There are a number of circular features that are either ice-modified shaft sinkholes or, less likely, large sub-glacial stream potholes modified by subsequent scour. At Site #2 on the sheet, there is a particularly rugged, scoured terrain that could be the ruin of a small karst. It contained one likely active sinkhole.

Given the barren ground (no protective vegetation) there appears to be surprisingly little felsenmeer (frost shatter) on these scoured surfaces except at the higher elevations.

This appears to be an ancient glaciokarst that is largely inert today. It has technical appeal to specialists because of its preservation in extreme climatic conditions. In particular, it will be interesting to examine the effects of global warming, which may reactivate the epikarst.

3.7. Northern Mackenzie Mountains

3.7.1. General Description of the Region

The significant karst here is contained on 1:250,000 topographic Sheets 96D – Carcajou Canyon, 96E – Norman Wells, 106A –Mount Eduni, 106G – Ramparts River, and 106H – Sans Sault Rapids. A map showing the karst features in the Northern Mackenzie Mountains Region can be seen in Appendix B.

The heart of the karst is on the Carcajou Canyon and Norman Wells sheets, which contain the core features of the Geopark that has been proposed along a line centred on the Canol Heritage Trail (Ford 2008). The karst landforms and groundwater features, such as springs, are illustrated extensively in the Ford (2008), pages 131-229, and a majority of them are explained and analysed in detail in a PhD thesis by Jim Hamilton (1995). Details will not be repeated here. The mapping on the sheets is based on our combined field experience; however it is almost certainly incomplete. The distribution of sinkholes, in particular, is generalized.

The principal karst landforms are on the Mount Kindle dolomite, the Bear Rock breccia and the Hume limestone. The Franklin Mountain dolomite is well exposed in the Dodo and Katherine Canyons, displaying colourful rock pinnacles in their walls. However, it is less significant as a host of karst landforms than it is in the Norman Range and the Low Plateaus. The Saline River Formation is also exposed in Dodo Canyon: there are no landforms in the salt but major block slumping is associated with its subsurface dissolution and salt-rich springs rise at the mouth of Carcajou Canyon.

3.7.2. Specific Description of Features and Areas

3.7.2.1. Sheet 96D – Carcajou Canyon

Site #1 is the Ration Creek Sinkhole, recommended for protection because it is an outstanding example of a large progressive collapse in steeply dipping strata; see Ford (2008), pages 132-4.

Site #2 is the Moraine Polje, with a notable river sink cave and a spectacular spring 1400 metres downstream. It is recommended for special protection or incorporation within the proposed geopark; see Ford (2008), pages 146-156.

Site #3 is the never glaciated, sub-arctic tundra of the Plains of Abraham and the Stony Plateau. These are magnificent examples of frost action producing patterned ground (polygons, stone stripes, lobes, etc) on dolomites. There are altiplanation terraces that indicate that there is local karst groundwater activity along the rims of small scarps and a few small sinkholes elongated along joints; see Ford (2008), pages 160-166. Site #3B is a very beautiful example of a karst steephead, with the modern springs sustaining a small oasis in the frost tundra. It was adapted by a small cirque glacier during the last glaciation, leaving behind a tiny terminal moraine; Ford (2008), pages 167-8.

Site #4 is the ‘Bonus Lake Karst’ (unofficial name), a karst greatly modified by glacial scablands erosion. It has excellent examples of corridors, sinkholes, estavelles (seasonally reversing sinks/springs), the disappearing Bonus Lake, and The Grotto, a relict river cave now blocked by frozen silts., It is analysed in detail in the Hamilton PhD thesis (1995) and summarized in Ford (2008), pages 135-145.

Area # 5 has many sinkholes and small lakes draining underground between the Bonus Lake karst and Carcajou Canyon. They have not been visited on the ground by the author’s field parties because they were deemed less significant than the other sites on this map sheet. A photo record and minimal field study is recommended.

Site #6 is the Pyramid Lake Polje. The lake and its feeder streams are drained underground along a syncline in the Franklin Mountain dolomite. The springs are on the right bank of the Little Keele River. They are studied in detail by Hamilton (1995) and see Ford (2008), pages 169-171.

Site #7 is the Falls of the Little Keele River, at the stratigraphic top of the Mt Kindle dolomite, with the Breccia above. They are very colourful; see Ford (2008), page 172.

Site #8 is the Dodo Dry Canyon, the former head of Dodo Creek whose waters were diverted into the Little Keele River by glacial action. Local drainage into the canyon now passes entirely underground to unknown springs. There are sinkholes, seasonal lakes, and sections of paleokarst, plus magnificent cliffs and talus slopes of Mt Kindle dolomite; see Ford (2008), pages 173-9.

Site #9 is the principal canyon of the Carcajou River, which here is diverted for 30 kilometres along a major glacial spillway channel. There are frequent sinkholes in Bear Rock and Hume strata on the dipping plateau behind its eastern wall; see Ford (2008), pages 213-4.

Site #10 is the Dodo Drape Karst, developed on the Breccia between Carcajou Canyon and Dodo Canyon. It is drained underground to a fragment of the spillway between the two canyons, where the stream sinks again and resurges at the mouth of Carcajou Canyon. It represents the distinctive kinds of karst landforms developed on the Breccia at their best, and is possibly a unique landscape; see Ford (2008), pages 199-208.

Site #11 is the Dodo West Pavements, the finest glaciated dolomite pavements the author has seen in any arctic or sub-arctic environment; see Ford (2008), pages190-8.

Site #12 is that of the springs at the mouth of Carcajou Canyon. Chemically and thermally, they are the most varied waters noted on this Sheet, temperatures being as high as $+8^{o}$ C. The Hamilton PhD thesis (1995) gives full technical details and see Ford (2008), pages 209-211.

Site #13 is representative of the many sinkholes and fragments of glacial spillway, dolomite pavement, and drape karst landforms in Mt Kindle, Bear Rock, and Hume strata that extend northwest onto Sheet 96E; see Ford (2008), pages 215-9.

3.7.2.2. Sheet 96E - Norman Wells

This sheet includes the downstream and northwest extremities of the northern Mackenzie Mountains karstlands, extending from the mouth of Dodo Canyon to the 'Great Fan' (unofficial name) on the Grafe River. The karst features are rugged sinkholes and draped topography on the Breccia, with foundering and some lesser sinkholes on the overlying Hume limestone. The corridor symbols in red ink and the 'br' notation indicate the dissected remnants of a glacial spillway that is now largely dry and drained karstically; see Ford (2008), pages 199-227 for details.

3.7.2.3. Sheet 106A – Mount Eduni

Tightly folded lower Paleozoic and Proterozoic rocks predominate in the Canyon Ranges on this sheet and support no karst.

Area # 1 is the northwest extension of the Stony Plateau found on the Carcajou Canyon map sheet. The highland arctic tundra surface on the Mt Kindle dolomites is similar to that of the Plains of Abraham. This sector was only briefly checked on the small scale air photos and has not been visited by the author. It is presumed to display the same range of periglacial and of subdued karstic features as are found on the Plains and the southern Stony Plateau.

Site #2, Snail Spring, is an isolated spring at the southern end of a sharply folded, plunging synclinal structure in the karst rocks but well to the west of the main karst areas. It is located and named on the topographic maps and thus will be locally prominent. It is presumed to be of karst origin but the author has no details.

3.7.2.4. Sheet 106 H – Sans Sault Rapids

Here only the area south of the Mackenzie River is being considered. That to the north is discussed in Section 3.5.2.7.

Area #1 denotes the western extremities of the main northern Mackenzies karst that is centred on the Carcajou Canyon sheet. At its southern edge is a small outcrop of the Stony Plateau dolomite surface. No distinctive sinkhole features were noted.
To the north, along the very abrupt edge of the Carcajou Range, there is a scattering of small sinkholes marking the western end of the Breccia karst terrain.

Site #2 is a small patch of possible dolomite pavement like the Dodo West pavement but smaller in extent. There is a large, fresh, and arcuate landslide to its east.

The most striking karst on this Sheet belongs to a series of outlying ridges north of the main Mackenzie Mountains front, the Imperial Hills. These extend for some 70 kilometres along the Mackenzie Valley, south of the River and rising 300 to 500 metres above the general elevations of the Valley. The eastern end of the Hills is within the Norman Wells sheet, 96E, but the most significant landforms are on the Sans Sault Rapids sheet. The principal strata are the Bear Rock breccia, with broken and disrupted Hume limestone on the flanks. In many respects, the karst of the Imperial Hills is like that on Bear Rock itself. The major karst landforms include some sharp fresh sinkholes, which are quite widespread. The author has never seen the Imperial Hills himself but helicopter pilots have often mentioned them when he has stated his interest in fresh and active karst. There are larger closed depressions including turloughs and permanent lakes (e.g. Imperial Lake itself) that drain underground. The greatest depression is more than five kilometres in length. Elsewhere there are blind valleys, clusters and scatterings of funnel sinkholes, and a few small patches of bogaz karst. There are probably natural arches and the draped topography typical of the known Bear Rock landscapes in the Carcajou Range but the scale of the air photography does not permit their identification; however Yellowknife Geologist Toon Pronk (2008) confirmed the presence of at least 2 natural arches in this area.

The Imperial Hills should be considered to be a priority site for more detailed studies, including field studies. It is a complex karst terrain, some parts of which may be developing quite rapidly today.

3.7.2.5. Sheet 106 G – Ramparts River

On the Ramparts River sheet, the Canyon Ranges are dominated by clastic rocks or limestones and dolomites that are less soluble due to high clay and silt contents. Little or no karst was detected along sample air photo traverse lines. Just one cirque lake appeared to be draining underground.

In reality, there are probably more karst features to be found but it is thought unlikely that they will be as significant as those further east.

4. Significant Karst Terrains in the Northwest Territories

4.1. Criteria to Gauge Significance

Two criteria have been used for this first assessment of the significance of the karst lands in the Northwest Territories:-

1. *Are either the individual landforms or their regional assemblages in the Northwest Territories significant at a regional scale?* Is their quality and interest of the karst landforms and the karst groundwater system development within the given region? Do individual landforms (e.g. sinkholes) display a variety of good quality morphology over an appropriate range of scales? Does a given form develop on a variety of karst rocks (limestone, dolomite, etc), and in a variety of structural settings, exhibiting significant contrasts? Are there a variety of landforms at different scales (pavement, sinkholes, turloughs, etc)? Do the individual landforms and their assemblage together in the region contribute to our understanding of processes of karst (and competing) development in the prevailing environmental conditions? Are they likely to contain records of previous and different environmental conditions? Are the landforms in themselves, and the karst system organization that creates them, aesthetically pleasing, attractive to visitors?

2. *Are either the individual landforms or their regional assemblages in the Northwest Territories significant at the global scale?* Are they :
   a. Good to very good examples of landforms and types of assemblages already known elsewhere that will contribute to our understanding of the generic development because they widen the range of rock types and/or environmental (climatic, ecologic) settings in which development is found to occur; and/or
   b. Display landforms and/or assemblages that are new to karst geomorphic and hydrogeologic studies, or extend the range of known karst lands to geographic regions previously considered unsuitable for development of karst.

4.2. Applying the Criteria –Areas of Established Global Significance

In applying the above criteria, it is suggested that the Northwest Territories contains at least four major assemblages of karst landforms and hydrogeologic systems that are of global significance. Two are Plateau and Lowland Karsts and two are Mountain Karsts.

4.2.1. The Southeastern Region

The Southeastern Region has long been recognized internationally because of the protection and publicity given to Wood Buffalo National Park. The author rates it as “Significant” at the world scale because of the quality of the collapse sinkhole landforms and the simplicity of the hydrogeologic organisation. Much of the finest development lies within the existing National Park. There may be a good case for establishing an interpretation centre at Salt Mountain outside of the Park if one does not already exist there.

4.2.2. Smith Arm, Great Bear Lake, and the Franklin Mountains Region

The Low Plateaus and Hydration Ridges between Smith Arm, Great Bear Lake, and the Franklin Mountains east and northeast of Norman Wells are rated "Very Significant" at the world scale by the author. This is because they incorporate an exceptional variety of landforms and hydrogeologic organization that is expressed in the three contrasted core areas: Mahony Dome, Tunago Dome, and the Lac Belot, Tunago Lake, Breccia Karst, and the Hydration Ridges. Together they form a geographic assemblage that is unique in geomorphology. It cannot be matched anywhere else on the planet and is certainly worthy of consideration for nomination as a UNESCO World Heritage property.

4.2.3. South Nahanni Region

The mountain and high plateau-canyon karst lands of the South Nahanni region of the southern Mackenzie Mountains are "Very Significant" at the world scale, again displaying combinations of unique features and outstandingly good examples of more standard landforms and hydrogeologic systems in a sub-arctic setting. All of these karst lands lie within the expanded area of the Nahanni National Park Reserve.

4.2.4. Northern Mackenzie Mountains Region

The mountain and high plateau karst of the northern Mackenzie Mountains that is centred on the Canol Heritage Trail area and promulgated in the Ford (2008), pages 135-231, is "Very Significant" at the world scale. It contains excellent examples of standard landforms plus others that are unique within a sub-arctic high tundra to boreal forest setting. It displays the variety associated with almost the full range of karst rock types and has many scenes of great aesthetic appeal. It is worthy of nomination for UNESCO World Heritage status but has been suggested for International Geopark status as a more rapidly attainable goal in the near term.

4.3. Northwest Territorial Karst Areas Where the Significance is Not Yet Well Established

There are three important karst areas where the significance of the landforms and hydrogeologic systems that are not yet satisfactorily established for differing reasons: the Franklin Mountain Ranges, the Sinking Streams of the Horton River, and the Imperial Hills.

4.3.1. The Franklin Mountain Ranges

The Franklin Mountain Ranges were overridden by the Laurentide Ice Sheet advancing from the east. The head-on collision of flowing glacier ice with steep-fronted mountain barriers of carbonate rocks has created complex landscapes in which karst or surface stream action can prevail during interglacial times and glacier erosion with modification or destruction of all prior landforms can prevail during the glaciations. The morphology of the Norman Range, which was completely buried under deep ice flowing westwards on more than one occasion, is the finest mountain and mountain-karst ice scour topography that the author has seen (see Ford (2008), pages 36-68). Presentation by the author of these findings at international conferences, for example the annual meetings of the European Geosciences Union at Vienna in April 2008, has attracted great admiration and requests for copies and further lectures. There is no similar landformsl in the Scandinavian countries or the central Ural Mountains of Russia, areas where one might go to find equivalents. The northern Urals are another candidate competitor but appear to be largely lacking in karst rocks.

The Franklins are not rated here, however, because their more extensive southern sector, the McConnell Range, has not been studied in any detail. As this Range includes both the Nahanni limestone (which is the key karst formation in the Nahanni) and the Bear Rock breccia and Mt Kindle dolomite (key formations in the northern karsts) it should be evaluated before full ratings are attempted.

4.3.2. The Sinking Streams of the Horton River

The Sinking Streams (Fluviokarst) of the Horton River (described in Section 3.6.2.1.) came as an unexpected surprise to the author. There are a large number of streams sinking underground into what must be well established karst aquifers. Yet the environment is very hostile; it is cold and dry with deep permafrost, strata that are the least soluble of the standard karst rocks, and low hydraulic gradients to drive the underground water circulation. A long record of inheritance is suspected, possibly pre-dating the in-growth of the permafrost. This area will be of substantial interest to karst scholars and groundwater hydrologists worldwide.

4.3.3. The Imperial Hills

The Imperial Hills (described in Section 3.7.2.4.) are comparatively modest in their extent and their height above the Mackenzie River flood plain but appear to encapsulate many of the karst and other processes at work on the Bear Rock and Hume strata elsewhere, with active sinkhole formation, sinking lakes, turloughs, etc. They merit field study of the karst phenomena.

4.4. The Horseshoe Lake Glaciokarst Depression, Iverson Range - a unique landform?

The Horseshoe Lake glaciokarst depression of the Iverson Range is described in Section 3.3.2.4. The author, a leading authority on the world’s alpine karsts, has never seen or heard of anything quite like it before. It warrants a field survey, which might also include the remainder of the Iverson Range because it is short in length and contains other karst features such as pavements, bogaz, and active sinkholes on the Nahanni Limestone.

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Appendix A. List of 1:250,000 Map Sheets Appraised

Sheet Number	Name	Full Survey	Sample Traverses
85A	Klewi River	X	
85B	Buffalo Lake	X	
85C	Tathlina Lake	X	
85D	Kakisa River	X	
85E	Mills Lake		X
85G	Sulphur Bay		X
85J	Yellowknife		X
85K	Rae		X
85L	Willow Lake		X
85M	Lac La Martre*		X
95A	Trout Lake*		X
95B	Fort Liard	X	
95F	Virginia Falls	X	
95G	Sibbeston Lake	X	
95I	Bulmer Lake	X	
95J	Camsell Bend	X	
95K	Root River	X	
95M	Wrigley Lake	X	
95N	Dahadinni River	X	
95O	Wrigley	X	
96A	Johnny Hoe River*		X
96B	Blackwater Lake	X	
96C	Fort Norman	X	
96D	Carcajou Canyon	X	
96E	Norman Wells	X	

Sheet Number	Name	Full Survey	Sample Traverses
96F	Mahony Lake	X	
96K	Lac des Bois	X	
96L	Lac Belot	X	
96M	Aubry Lake	X	
96N	Lac Maunoir	X	
96P	Bloody River		X
96O	Horton Lake	X	
97A	Erly Lake	X	
97B	Simpson Lake	X	
97C	Franklin Bay		X
106A	Mount Eduni		X
106G	Ramparts River	X	
106H	Sans Sault Rapids	X	
106I	Fort Good Hope	X	

* Mapsheets Reviewed but not documented in the report:

Sheet 85M (Lac La Martre): Extends from 63-64 N, 118-120 W. It contains the Cartridge Plateau, which was a site of potential interest but on review lacked any of the potential features at this scale.

Sheet 95A (Trout Lake): Extends from 60-61 N, 120-122 W. It is a swampy lowland area between areas of karst but, at this scale, apparently with none of its own.

Sheet 96A (Johnny Hoe River): Extends from 64-65 N, 120-122 W. Covering the area just southwest of McVicar Arm of Great Bear Lake. It is very low relief terrain buried in glacial deposits of various kinds. There are possibly some small scale karst groundwater basins and a few tiny sinks and springs in the region but they were not detectable on the 1:50,000 scale air photos that were scanned. If there is any karst it will not be significant when compared to that on the other sheets in this area.

Appendix B. Maps of Karst Features in the NWT

Go to http://www.nwtpas.ca/science-karst.asp to download copies of the maps.