Report upon a Survey of Karst Landforms

around Norman Wells, Northwest Territories

for the NWT Protected Areas Strategy
Department of Environment and Natural Resources
Government of the Northwest Territories
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by

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Ford, D. 2008. Report Upon a Survey of Karst Landforms around Norman Wells, Northwest Territories. Prepared for the NWT Protected Areas Strategy, Department of Environment and Natural Resources, Government of the Northwest Territories, Yellowknife, NT.

Short description of report (J. Wilson, ENR):

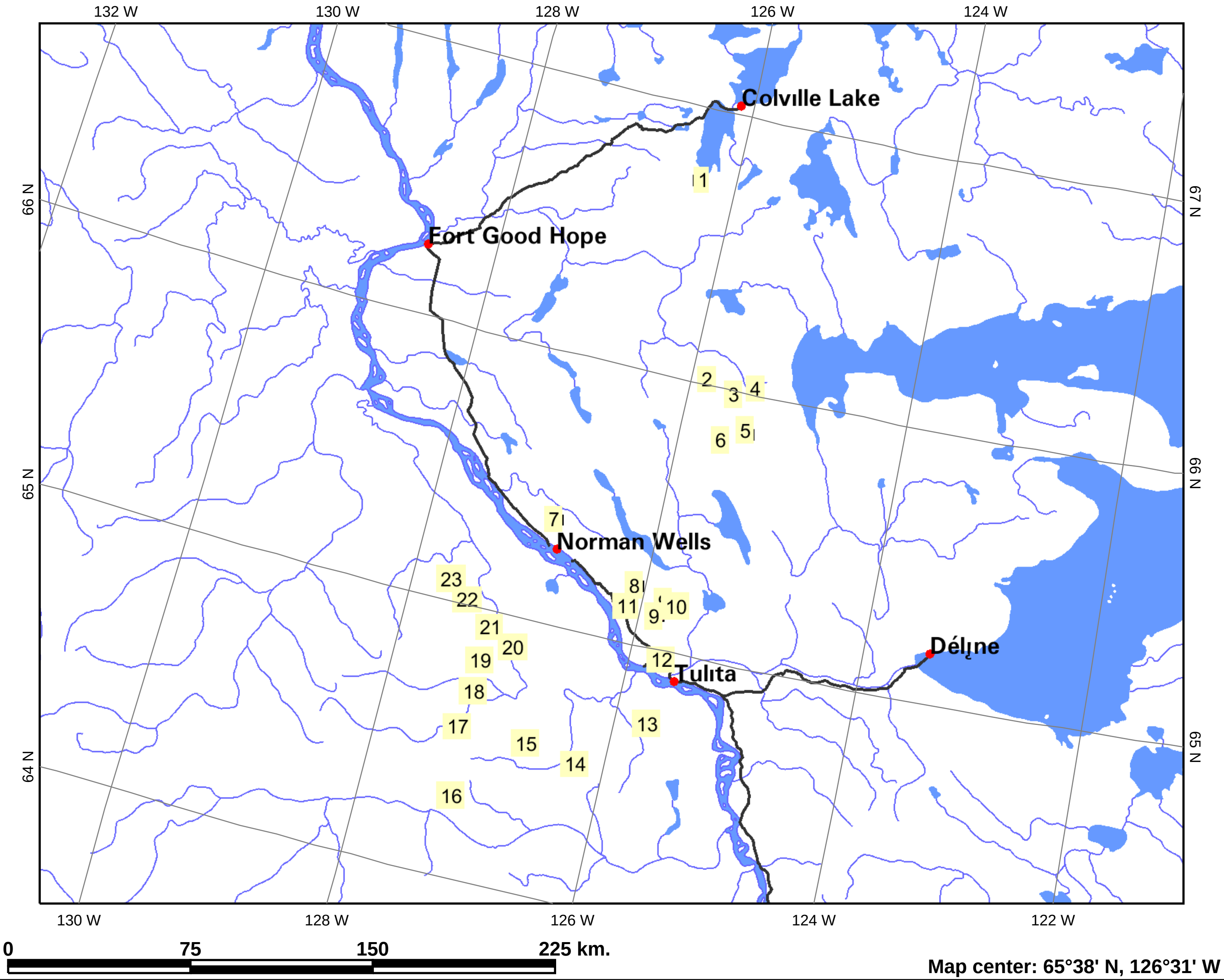
The Northwest Territories (NWT) has many interesting landforms known as **karst** topography. Karst landscapes form where rock dissolves in water (e.g., limestone), creating features like sinkholes, caves, dry valleys and gorges, turloughs and poljes (large depressions drained underground by sinkholes within them, which are periodically flooded when the underlying caves become swamped with water). Karst landscapes sometimes contain 'disappearing' streams or underground rivers. Karst landscapes often have spectacular scenery and unique communities of plants and animals. Understanding the geology and the flow of ground waters through karst rocks can help to understand the environmental effects of various land uses.

Dr. Derek Ford, one of the world's leading karst experts, came to the NWT in July 2007. He did 4 days of aerial surveys to locate, photograph, and describe some of the karst sites in the Sahtu region. This report describes what he found, and gives his recommendations for protecting some of the most important karst sites. The report includes many photographs and descriptions of the karst features he surveyed.

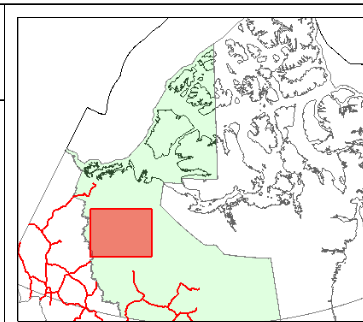
There are some very interesting and significant karst sites in the Sahtu region. Some of these overlap with protected areas, proposed protected areas, and proposed conservation zones.

- Dr. Ford recommends that several sites should be protected as outstanding examples of karst features, including the Vermilion Creek sinkhole (between Norman Wells and Tulita), some features of the Mahony Dome (sinkhole 142, turlough 110 and the Disappearing River, located north of Mahony Lake), and the Ration Creek sinkhole (west of the Mackay Range).
- Bear Rock (just northwest of Tulita) is found to be very significant for the variety and high density of its karst, and is recommended for protection.
- In the Canol Trail area, there are many features of exceptional quality and significance (from the Plains of Abraham to Carcajou, Dodo and Katherine canyons, including Pyramid Lake Polje, Dodo Dry Canyon, Dodo West Karst Pavements, Dodo Breccia Drape Karst, Great Fan Landslide, Western Great Spillway and Fan, as well as the Bonus Lake Scablands and Moraine Polje). Dr. Ford feels that these sites in the Canol Trail area are so significant that they should be proposed as a UNESCO International Geopark. A Geopark proposal here would have an excellent chance of achieving UNESCO World Heritage status, which would likely attract international tourism.
- Lac Belot Ridge and its associated karst (located between Colville Lake and the Hare Indian River) were not surveyed in 2007. Dr. Ford recommends that this area should be studied because it is associated with the Sahtu story of Neyádalín (the Underground River) and is probably a very significant karst.

Approximate locations of some Sahtu karst features



Map center: 65°38' N, 126°31' W



Legend

- NWT Communities
- Roads (NRN)
  - Expressway / Highway
  - Winter
- Rivers (2M)
  - Rivers Single line
  - Rivers Double Line
- Admin Islands Atlas
  - Ocean
- Lakes (2M)
  - Lakes
  - Lakes

N

Scale: 1:2,535,969

This map is a user generated static output from an Internet mapping site and is for general reference only. Data layers that appear on this map may or may not be accurate, current, or otherwise reliable. THIS MAP IS NOT TO BE USED FOR NAVIGATION.

Notes: These are approximate locations of some features mentioned in 'Ford, D. 2008. Report Upon a Survey of Karst Landforms around Norman Wells, NWT.' Digitized by J. Wilson, ENR.

Numbers used to label some Sahtu karst features

Lac Belot Ridge	1
Sinkhole 142	2
Disappearing River	3
Hare Indian River Valley springs	4
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Carcajou Canyon	20
Dodo West Karst Pavements	21
Dodo Breccia Drape Karst	21
Dodo Canyon	21
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Katherine Canyon	22
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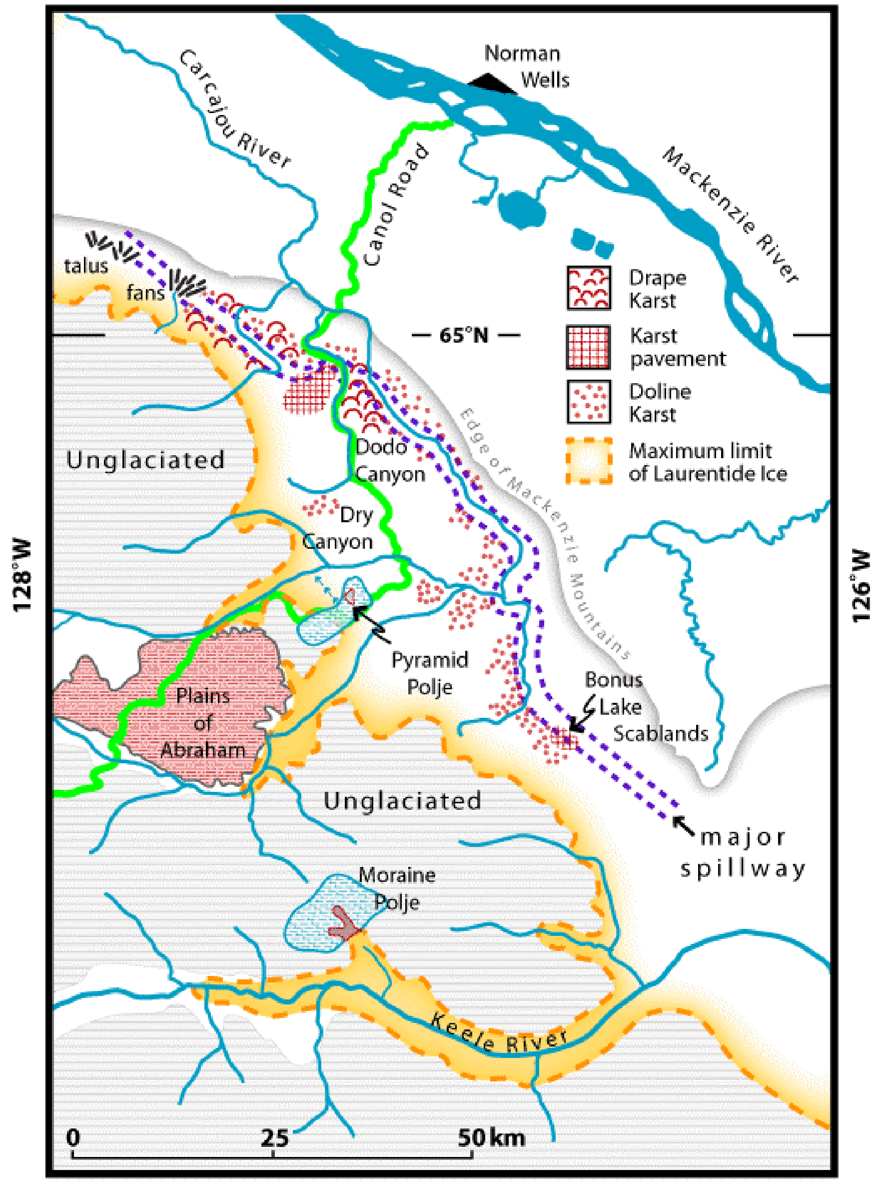

Schematic of karst in the Canol Trail area (D. Ford, pers. comm., April 2008).

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Executive Summary with Recommendations

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Karst geomorphology is the study of natural landforms and caves created by the dissolution of comparatively soluble rocks. **Karst hydrogeology** studies the flow of ground waters through the karst rocks, via the systems of caves and micro-caves (mouse-sized) created by solution along paths through fractures in the rocks.

At the surface the principal types of karst landforms represented in the region around Norman Wells are: (i) at small scale, **karren** – solutional pits, runnels and micro-shafts developed on bare rock surfaces or under shallow soil cover. Individuals are rarely greater than a metre or two in size but they usually occur in clusters or wider spreads that may cover many ha or even square km. (ii) at intermediate scale, **sinkholes** – ranging from a few metres to hundreds of metres in diameter and up to 100 metres or more in depth. There are two principal origins – first by surface runoff water dissolving a funnel-shaped depression downwards that delivers flow to the underground cave systems – second, by collapse of a cave upwards to the surface. Both types are well represented in the Norman Wells region. (iii) at large scale, **dry valleys and gorges** where dissolution has captured original surface streams and diverted them underground with the result that surface channels are abandoned either permanently or at all times except high flood periods when there may be overflow. **Turloughs** and **poljes** are large, topographically closed depressions drained underground by sinkholes within them, that are subject to periodic flooding when the underlying caves become swamped with water. Both may accumulate alluvium that forms central flat floors around the sink points. Turloughs are rarely greater than 2-3 km in length. Poljes may be larger, in part because the flood waters are able to dissolve benches into the hills of soluble rock enclosing the depression.

Most types of rock are essentially insoluble in the very mildly acidic waters that occur naturally on the surface of the Earth. As a consequence, karst landforms and systems are not found everywhere; whole nations may be without any, e.g. Finland. However, they do underlie approximately 15% of the continental surfaces, and supply part or all of the water for more than 20% of the world's population. In descending order of solubility, the important karst rocks are (i) **salt** – so soluble that it survives at the surface only in the driest places; (ii) **gypsum and anhydrite** – only 1% as soluble as salt but that is sufficient for comparatively rapid dissolution so that their presence as layers within other rocks of little or no solubility induces broad scale collapse when groundwater can preferentially remove them; (iii) **limestone and dolomite** – the most widespread karst rocks. Limestone is the more soluble of the two (about 10% as soluble as gypsum) and worldwide is associated with the largest karst landforms, longest and deepest caves. Because of relatively low solubility, in many regions dolomite may exhibit few karst forms at the surface although there is efficient ground water flow through micro-caves beneath it. One of the most remarkable features of the Norman Wells region is that karst development is so substantial on its dolomites, which are the predominant karst rocks.

Karst rocks of the Norman Wells region

Karst rocks are very widespread. The oldest are found in the **Saline River Formation**, laid down in the Cambrian age more than 500 million years ago. As its name suggests, the Saline River Fm contains beds of salt that are sandwiched between beds of gypsum, and other rocks such as sandstone and shale (clay rock) that are insoluble. Salt is not exposed at the surface but ground water is able to reach and dissolve it deep underground in this region, creating rock collapse overhead, and occasional salt springs. Overlying this formation is the **Franklin Mountain Fm** (Cambrian-Ordovician), a dolomite deposit of thick to massive beds (layers) totaling 300 m or more. This rock is resistant to mechanical erosion processes and so forms strong cliffs. It is the predominant karst rock east of Norman Wells, where it is a bright white in colour. West of Norman Wells it can be a distinctive orange or yellow. Above this is the **Mt Kindle Formation** (Silurian-Devonian), another dolomite with thick to massive beds that can support great cliffs. It totals more than 500 m in thickness and is grey to rusty red weathering. It is succeeded by one of the most remarkable and unusual karst rocks found in all of North America, the **Bear Rock Formation** (Devonian). Deep beneath Norman Wells this is a sequence of dolomite and gypsum layers but at shallow depth and everywhere where it is exposed at the surface, solution of the gypsum has collapsed the dolomite into a chaotic rubble of blocks of all sizes (termed a **breccia**) that has been re-cemented quite strongly by limestone (calcite) carried by the ground waters. The author has only seen one other breccia as extensive as this, in the Yucatan region of Mexico where it is believed to have been created by the Chicxulub meteorite impact into limestones. The Bear Rock Breccia supports some karst that is truly unique in form. Overlying the Bear Rock Breccia is the **Hume Formation** (Devonian), approximately 120 m of cliff-forming limestones. It is succeeded by sequences of younger sedimentary rocks that are mostly insoluble but mechanically weak, with the consequence that karst collapses underneath may propagate through them to the surface.

Ice Age and Cold Climate Factors

All land east of the frontal ranges of the Mackenzie Mountains were overridden by the Canadian continental ice sheet during the last glaciation. This eroded many earlier karst landforms and laid down deposits of glacial debris (till) that have slowed down karst processes locally in the post-glacial period. The ice was able to penetrate quite deeply into the Mackenzies along major valleys such as that of the Keele River, but in the west there are high mountain terrains on the dolomites that were never glaciated.

In the modern climate the entire region is technically permafrozen to depths of 50 m, or more at higher altitudes. Freezing temperatures and presence of ground ice limits the opportunities for water to penetrate underground and dissolve rocks there. A result is that the local hydrologic and hydrogeologic conditions can vary considerably between locations only a few metres or tens of metres apart, which greatly increases the mixture and variety of karst and other landforms able to develop at the surface.

Karst Terrains east of the Mackenzie River

A. The Norman Range from Norman Wells to Bear Rock.

The Norman Range is formed primarily in dolomites of the Franklin Mountain Fm but towards Bear Rock and at the Rock itself is replaced by the Breccia and overlying Hume limestone. All were covered and scoured by glacier ice. There are many attractive **glaciokarst** (ie. polygenetic) sinkholes and other karstic forms on the dolomite but they are widely scattered and so do not form conveniently defined physiographic units.

Bear Rock itself is an outstanding example of glaciokarstic landform development that includes many sinkholes and larger closed depressions, some with permanent lakes that are drained underground at their overflow points, plus some striking pinnacle clusters, and a major group of perennial springs that display big ice build-up (icings) in winter. Bear Rock is at present recognised as a site of special cultural interest.

Nearby is the Vermillion Creek Sinkhole, which is the finest example of a simple cylindrical collapse landform known anywhere in Canada. It is fresh and young in appearance and elliptical in form, measuring 120 X 60 m plus 40 m deep to the surface of a pond in it. The vertical walls are of thin limestones and shales of the Canol Formation; the collapse was caused by dissolution in Bear Rock gypsum or Saline River salt (or both) beneath it.

Recommendation 1 – that Bear Rock be protected as an outstanding example of mountainous karst overridden and modified by continental glacial action. This protection may be integrated with the cultural protection that is proposed.

Recommendation 2 – that Vermillion Creek sinkhole be protected because it is the finest example of a fresh collapse sinkhole known in Canada. This protection may be
coupled with protection of the Ration Creek Sinkhole described below, which is an outstanding example of a karst collapse in a more complex geologic setting.

B. The Hare Indian River plateaus between the Norman Range and Great Bear Lake.

These are broad, very flat-topped plateaus rising a few hundred metres above the Hare Indian River and outlying lakes draining to it or to Great Bear River. The plateaus are up to a few hundred square km in extent, formed on flat-lying dolomite beds of the Franklin Mountain Fm with some very local occurrences of Mt Kindle or Bear Rock dolomites. The Hare Indian River bisects the country, following a large valley (a glacial spillway) that was created by a mega-river discharge from a glacier occupying Great Bear Lake. The most significant karst drains from the plateaus to series of springs in the valley. This area was first studied by R.van Everdingen, National Hydrological Research Institute, in the later 1970s. He reported some 1000 sinkholes and 40 springs.

The Mahony Dome on the south side of the Hare Indian valley displays the best karst landforms. It has many sinking streams, shallow sinkholes and turloughs and one spectacular example of a river abruptly plunging underground, the ’Disappearing River’ of van Everdingen. Turlough # 142 (van Everdingen's numbering scheme) is the best example of a mature turlough, i.e. one that fills to an established high water line during the melt season and then is drained via one or a few principal sinkholes in the floor. It is ~3 km in length and 2 km in width. Turlough #110 is a larger depression extending for ~6 km from the southeast (or upstream) end to the northwest (downstream). It collects melt water and runoff from all sides but chiefly easterly. In its early days it will have flooded to form a single lake more than 20 square km in area that was drained by only one or two sinkholes. Karst development has been quite rapid so that today it is drained by 40 or more separate sinks of varying size and shape. Local areas still flood annually but much of the depression is desiccated. Shrubs and forest are advancing into it. Individual sinks can be spectacular, vertically walled mini-canyons ten metres deep with bright white dolomite walls. The Disappearing River has a principal sinkhole, #86B, approximately 100 m in length, 40 m wide and 25-30 m deep from the rim to the water sink. Entering it, the River first drops down a small waterfall and then builds a detrital fan out into the depression. There are two overflow channels leading to similar sinkholes. It is believed that the water must drain to some attractive, peaty springs a few km distant and one hundred metres lower in the Hare Indian valley.

Recommendation 3 – that the turlough, Sinkhole #142 be recognized and protected as the most outstanding example of a mature turlough in the region.

Recommendation 4 – that the adjoining drainage basins of Turlough #110 and the Disappearing River be recognized and protected as outstanding examples of a turlough in the Old Age stage of disintegration into multiple sinkholes and of a sinking karst river. Further that the location of their spring outlets be determined by ground water dye tracing and also protected.

C. Lac Belot, Belot Ridge and the Legend of Neyadalin, the Underground River.

Lac Belot is a lake of >300 square km lying between Colville Lake to the north and the Hare Indian River to the south and southwest. Van Everdingen made no studies there and so it was largely overlooked in the 2007 field review. Our attention was drawn to a Protection Proposal by members of the Colville Lake community that refers specifically to the 'Legend of Neyadalin'. This is most colourful; two brother paddle their canoes into a sink hole draining all the water of Lac Belot, follow an underground river beneath Belot Ridge and emerge via two different springs in cliffs some 20 km distant on a north-bank tributary of the Hare Indian River.

From the topographic maps it appears that Lac Belot does drain underground towards Belot Ridge. The Ridge itself is one of the most remarkable karst features east of the Mackenzie, a long, straight and narrow landform probably created by rapid hydration of anhydrite in the Bear Rock Fm when a glacier front lay alongside and poured melt water in at the close of the last glaciation: when water is added, anhydrite swells 15-30% in volume and converts to gypsum. Volume increase underground here caused the land to rise and burst open along the ridge line, which is about 60-80 m in height. There are large karst sinkholes depicted on the topographic maps to the southwest, around the springs of the Neyadalin legend.

Recommendation 5 – that studies of Lac Belot Ridge and the adjoining karst in Bear Rock strata be undertaken, including tracing and interpreting the course of the ground water, with the intent of considering a karst protected area to be associated with the Neyadalin Legend protection proposals.

Karst Terrains west of the Mackenzie River.

The Report first discusses some outlying areas, and then focuses on the karst found along or close to the Canol Heritage Trail between the 'Plains of Abraham' at the upstream or southern end of karst rock outcrops and the exit of the principal creeks and rivers into the Mackenzie Valley at the northern end.

A. The Mackay Range, Ration Creek Sinkhole and the 'Bonus Lake' Karst.

The Mackay Range stands out as an isolated mountain range in the plains on the western bank of the Mackenzie River. It is an upfold of Mt Kindle dolomite and Bear Rock breccia with Hume limestones on the west flank and an important fault through the middle. There is a large central closed depression west of the fault. The Range rises abruptly to heights of 300-400 m above the plains. All interior areas of the Range are drained karstically to small springs around the perimeter. Very steeply dipping Bear Rock strata along part of the east face produce beautiful talus fans with torrential debris flow channels in some of them. Accumulation of ground ice in the aprons of some fans have converted them into rock glaciers, a distinctive periglacial (permafrost) landform. The Mackay Range stands out strongly in the Mackenzie Valley lowlands and exhibits many attractive features such as the talus, patterned ground and springs with floral oases. However, its landforms are similar to those of Bear Rock itself but not as varied or well developed in many respects, so it is not recommended for special protection.

Ration Creek Sinkhole (N 64 31.20', W 126 15.30', water line at 380 - 400 m above sea level) appears abruptly on an overflight, breaking up the crest line of a glacially rounded ridge in the dolomites west of the Mackay Range. It is another spectacular collapse landform but, in contrast to that of Vermillion Creek, is in steeply dipping Mt Kindle dolomites and Bear Rock breccia, so that its detailed form is quite different. It is some hundreds of metres in diameter and more than 80 m deep to a small pond. It is believed to drain via sinks at the edge of the pond to springs a few km distant in the Little Bear River valley.

Recommendation 6 – that Ration Creek Sinkhole be recognised and protected as an outstanding example of collapse sinkhole formation in mixed and deformed karst rocks.

The karst of “Bonus Lake” is the finest example of karstic adaptation of glacial ‘scablands’, which are giant potholes and scalloped depressions torn into bedrocks by very violent outbursts of glacial melt waters ponded up by ice dams that suddenly break.
The karst lies at the foot of the Mackenzie Mountains west of Ration Creek and is developed on the flank of a large glacial spillway entrenched in weaker shaly rocks.
Resistant limestones of the Hume Fm dip gently into the spillway, where flood action enlarged any prior karst landforms and scoured new river forms into the limestone and Bear Rock breccia underneath it. The lake is created by a large debris fan locally blocking the abandoned spillway. Although marked as a permanent lake on the topographic maps, it is in fact seasonal and is drained underground into the scablands karst. The ground water flows to springs several km further down the spillway that supply the headwaters of Grotto Creek. ‘Bonus Lake’ is an informal name given by the author when he came upon it unexpectedly during a reconnaissance flight into the Mackenzie Mountains in 1983; ‘Grotto Lake’ may be a more appropriate name in English. The partly drowned karst landforms along the lake shore have great aesthetic appeal, being rock-walled mini-lagoons with pinnacles, gravel beaches and spits that are scented with wild mint in the summer.

Recommendation 7 – that the Bonus Lake (or Grotto Lake) Karst receive the fullest available recognition and protection, either as a site on its own or as a component of an international geopark centred upon the Canol Heritage Trail.

(B) Moraine Polje.

This is a karstic take-over of a river basin ~90 square km in area that is a north bank tributary of Keele River, the major river lying just to the south of the main regions of karst interest in the Mackenzie Mountains. The basin is mostly high ground (above 1000 m above sea level) in the Mt Kindle dolomite. It had never been glaciated until, in the last glaciation, a tongue of the continental ice sheet pushed up the Keele River valley and emplaced a small but strong barrier of glacial debris (a ‘terminal moraine’) at a narrow point a short distance up the tributary. Upstream areas remained unglaciated but the waters were impounded behind the moraine. Moraine damming like this is commonplace in mountain regions but, almost invariably, the dam is broken because the impounded water rises, overflows and entrenches the moraine. Before overflow could occur here, the water opened a small, raw cave in the dolomite. By its route the water passes under the dam and bursts dramatically out of the valley wall downstream at a spring that looks as if it had been opened by a giant fist punching out the rock from the inside. It is unique in appearance in my experience, and karstic underpasses below moraine dams are also very rare phenomena. The spring is ~1300 m distant from the cave in a straight line. In 1983 the author and his party placed a tracer dye in the cave and recovered it at the spring five hours later, showing that there is a fast and efficient connection. Behind the dam an extensive floor of alluvium has accumulated up to the level of the cave and is seasonally inundated. Geomorphologically and hydrologically this basin has the form and function of a polje and is, in fact, one of the largest known in North America.

Recommendation 8 – that Moraine Polje be recognized and protected as a glaciokarst landform of outstanding quality and geomorphological significance.

C) Karst, Periglacial and Glacial Landforms of the Canyon Ranges from the Plains of Abraham to Carcajou, Dodo and Katherine canyons: recommended as the components of a possible UNESCO International Geopark that broadly follows the Canol Heritage Highway.

A traverse from the Plains of Abraham in the interior of the Canyon Ranges to the mouths of the canyons debouching into the Mackenzie Valley passes through a rich variety of sedimentary rocks and of geological structures. It begins in an area never glaciated but subject to intensive periglacial (cold climate) conditions during the glacial periods and still retaining deep permafrost today, passes through a narrow zone of older glaciations, into a mountain front sector overrun and scoured during the final glacial advances and then eroded with catastrophic rapidity by some giant melt rivers along the NW edge of the continental icesheet.

All of the karstic rocks mentioned in this report (limestone, dolomite, breccia and salt) can be observed undergoing modern dissolution along this traverse, and there are many other geomorphic processes vigorously at work on both the soluble and the insoluble strata. It is a region of outstanding geologic and geomorphic interest that also offers landscapes of considerable aesthetic appeal.

Individual karst and other areas of outstanding quality are presented in the sequence in which they are encountered on a journey along the Heritage Trail from a southern terminus on the Plains of Abraham to the mouths of three large canyons in the Mackenzie Valley lowlands.

The Plains of Abraham are an extensive plateau in the central unglaciated zone, formed of horizontally bedded dolomites of the Mt Kindle and Franklin formations. Elevations are generally between 1500 -1700 m asl, placing the Plains in the arctic tundra biozone. They drain to the Carcajou River and its tributaries, which are entrenched 500 m below them. The Plains exhibit a very wide variety of frost-sorted landforms and landscapes, including stone stripes, polygons, lobate flows and many others. Despite the severity of the climate there are some karst sinks on the plateau surface. Around its edges small springs have created some karst ‘steephead’ valleys, cirque-like landforms a few hundred metres in diameter that are cutting back into the plateau like cookie cutters.

This is the finest steephead topography I have seen in any alpine or periglacial region. The Canol Road crosses the Plains, passing by the crest of the best steephead valley.

Pyramid Lake is 15 km northeast of the Plains and at 786+/- m above sea level, fluctuating a little in level seasonally. It occupies an alluvial lowland, is drained underground karstically in the Franklin Mountain dolomite, and thus functions as a karst polje. It has a catchment basin area of 34.4 sq kms. The water sinks in a channel bed upstream of the lake, where it was dye traced to 'Horseshoe Springs' (unofficial name) with a flow time of four days (~1500+ m/day). The underground flow broadly follows a synclinal downfold in Franklin Mountain dolomites, i.e. this is a case of karstic polje flow being determined chiefly by geological structure rather than by a moraine dam as at Moraine Polje. The Canol Road passes through the basin.

From Pyramid Lake the Canol Road winds north across the Little Keele River (actually a tributary of Carcajou River), which has some attractive falls over Mt Kindle dolomites with colourful Bear Rock breccia uplands in the background. The region escaped the most recent glaciation and offers fine, cold climate, pedimented landscapes.

Dodo Dry Canyon is a magnificent feature. It was carved by the Little Keele River which was then diverted to Carcajou River by glacial action, robbing Dodo Creek of its principal headwater and leaving its upper canyon dry. It is developed in Franklin Mtn and Mt Kindle dolomites and minor Bear Rock breccia. The waters that it captures today all sink underground. The Canol Road uses the gentle southern end of the canyon but then diverts east to find an easier route to the north. There are sinkholes in the upper canyon above a steep bedrock step (a paleo-waterfall) and an intermittent lake below. The middle canyon is without water; an outstanding feature is the manner in which great aprons and fans of dolomite talus sweep in from either side. A further feature is the apparent occurrence of 'paleokarst' depressions and deposits in the cliffs. After deposition of the Franklin Mountain dolomite more than 400 million years ago there was a long period of karst erosion before deposition of the Mt Kindle dolomites began. Karst sinkholes formed and filled with bright buff, orange and yellow terrestrial sediments. The visual climax of Dodo Dry Canyon is its northern (downstream) end where it is more than 350 metres deep and talus fans converge from both sides, trapping a pretty karst lake between them.

Dodo Creek Canyon is entrenched across the flank of a major anticline (upfold) in the strata. As a consequence it first passes down through progressively older rocks to the crest of the anticline and then back up through them to its mouth. It is a very colourful journey as all strata from the basal Saline River Fm (bright red in places) to the uppermost Hume Fm (soft blue white) are encountered. The Canol Road followed the canyon; floods on Dodo Creek have destroyed most of it but the ruins of one big camp remain. They are at the head of the most dramatic section of the canyon, where bright orange Franklin Mountain dolomites with sharp pinnacles dip into the canyon floor and the more massive, dark grey and steeper cliffs of the Mt Kindle Formation appear behind them.

This is the deepest part of the canyon, the walls being more than 400 m in height. Downstream the canyon then passes through a striking portal into the multi-coloured Breccia which is eroded into many different forms.

Above the Canyon on the west side are the **Dodo West Pavements**, an extensive spread of Mt Kindle dolomites. They are ‘cyclic’ deposits of thick and strong beds, succeeded by weak thin beds like meat in a sandwich. Glacier ice of the last glaciation bulldozed the strata away along the weaker beds, creating a staircase-like topography.

Each strong bed surface that was exposed tends to have slightly different properties with the consequence that the delicate, small scale solutional landforms (karren) that have developed are never quite alike on any two beds. The West Dodo dolomite karst pavements are amongst the finest known anywhere in the arctic regions.

Between Dodo Canyon and Carcajou River Canyon that lies to the east of it, the Bear Rock Breccia is dissected by karst processes into a fantastical landscape termed the **Dodo Breccia Drape Karst.** It includes some landforms unknown in any other part of the world. Meltwaters from the continental ice sheet and then thousands of years of rain and snow melt have scoured corridors and sinkholes into the Breccia, destroying its softer parts and leaving more resistant, hardened surface crusts draped across ridges or sliding into sinkholes of many shapes and sizes. It is a chaotic ‘dissolve-and-drape’ topography. There are dry valleys, stream sinks, sinkholes with delightfully clear blue-green ponds, excellent examples of frost-patterned ground, and small springs from within the permafrost (‘intrapermafrost flow’) building winter icings. The Drape Karst drains to ‘Carcadodo Valley’, an important section of a great glacial spillway that was carved at the end of the last glaciation. Its springs feed a stream that sinks underground again on the rim of Carcajou Canyon, where it returns to the surface together with long-travelled regional groundwaters that discharge very salty waters at springs marked by salt-adapted vegetation.

After approaching within three kms of it goal, the Mackenzie Valley, the **Carcajou River** abruptly turns west for 24 km along the great spillway, following a canyon with walls more than 500 metres in height in Mt Kindle dolomites and Bear Rock Breccia. West of the Dodo Pavements the spillway is abandoned today, leaving a broad dry canyon carved into Mt Kindle dolomites**.** There is a most spectacular **‘rotational landslip’** in the north bank, where the spillway flood waters undermined the rock, bringing it down hundreds of metres in seven successive bedrock slices that rotated (tilted) backwards as they slid down. Slides on this scale are extremely rare in strong rocks such as the Mt Kindle dolomites. It is the finest example of a rotational slide I have seen anywhere in dolomites.

West of the slide the great spillway is a canyon adopted for a few km by **Katherine Creek**, a stream similar to Dodo Creek in size. It then has a final abandoned section that extends westwards for eight km until buried by fan deposits. It is carved primarily in the Breccia with uppermost beds of the Mt Kindle dolomites occasionally seen. Karst and frost processes have carved fantastical pillars, bridges and drapes into the rocks, and there are many sinkholes. A first spectacular fan consisting of a sequence of lobate debris flows building out in front of or piling on top of one another begins to bury the spillway, which then finally disappears beneath **“The Great Fan**”, the largest in the region. It is composed of bright white and pale buff debris from the Breccia.

Treated as individual sites of interest, the features emphasized in **BOLD** above are all worthy of protection as karst or other geomorphic and geologic features of exceptional quality and significance. However, as noted, the majority of these outstanding features are on the Canol Heritage Trail or very close to it. As a consequence

Recommendation 9 - is that consideration be given to placing all of these sites within one protected area that is linked together by the Heritage Trail between the mouth of Dodo Canyon and the southern end of the Plains of Abraham,

and

Recommendation 10 – is that because of the outstanding quality and universal significance of this combined protected area it be vigorously promoted nationally and internationally for recognition as a UNESCO International Geopark,

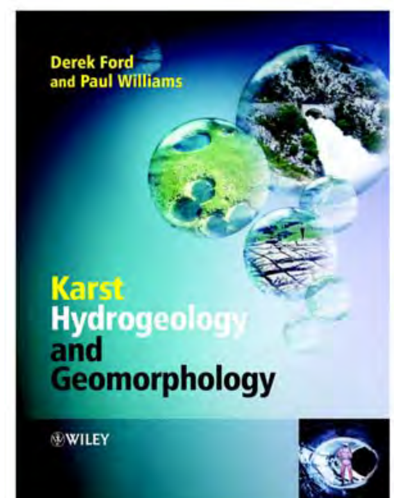
and further

Recommendation 11- that consideration be given to setting the boundaries of Geopark such that the Bonus Lake Scablands Karst and Moraine Polje can be included within it as well.

“Karst” – the term derives from a Serbo-Croat word ‘crs’, meaning ‘stony ground’.
The ‘classical’ karst area is in western Slovenia and adjoining Trieste, Italy. It was deforested by Roman times, and overgrazed with sheep and goats. Soil cohesion was destroyed and the soil washed into underlying micro-caves of solutional origin.

Karst geomorphology is the study of landforms and caves of solutional origin. Karst hydrogeology studies the flow of ground waters through the karst rocks.

The principal karst rocks are limestone and dolomite (moderately soluble and very widespread), gypsum and anhydrite (very soluble and quite widespread) and salt (extremely soluble and therefore seen at the surface only in very arid places such as Death Valley, California).



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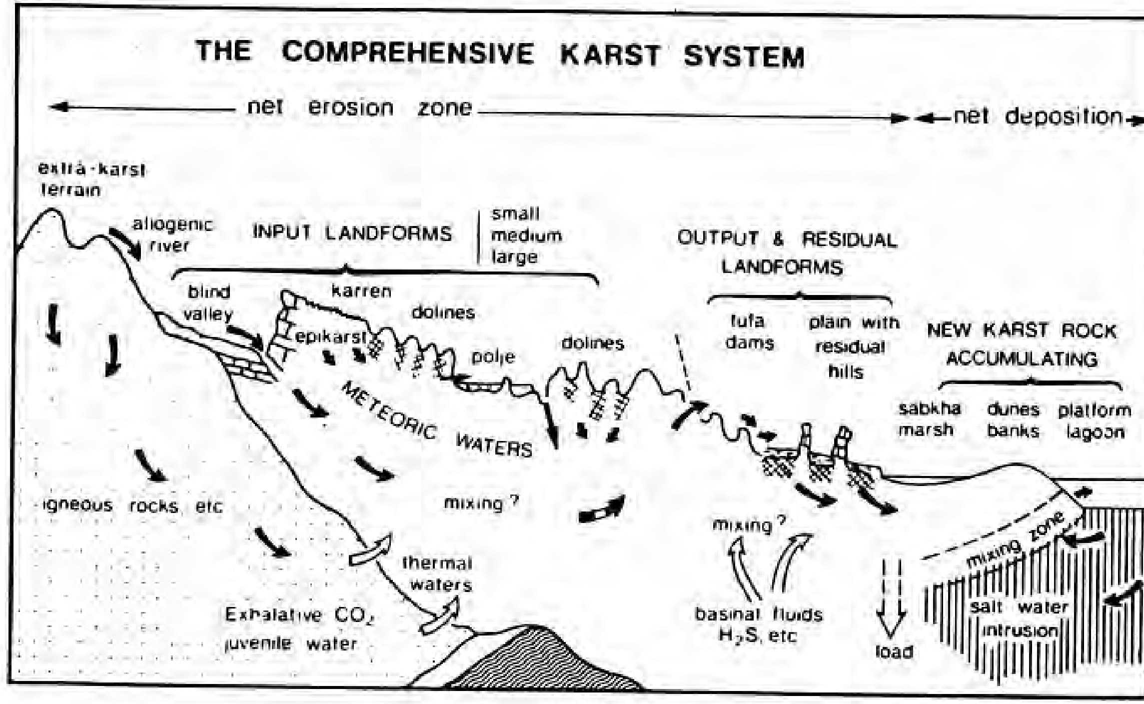
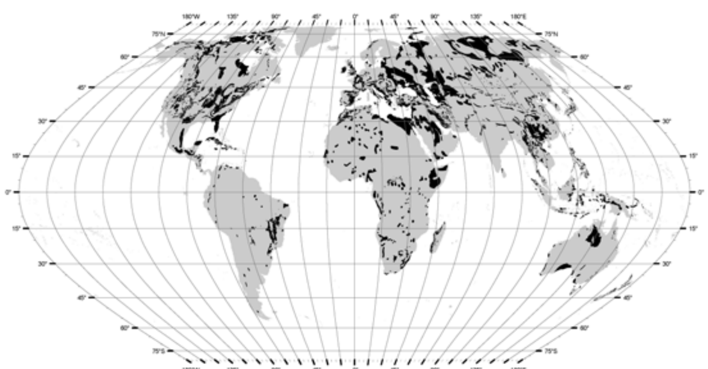
The karst system is complex, involving shallow and deep meteoric waters, salt waters and thermal waters of various origins. Two broad categories of landforms are recognised at the surface, both ranging in scale from mm to km. Underground, caves range from a few cm in diameter and length to large chambers and hundreds of kms of passages.





The global outcrop of limestone and dolomite is shown to the left. There is a much greater extent buried by other, insoluble, rocks.

20-25% of the world's population is partly to entirely dependent on karst ground water for its water supplies.

The reality of aqueous dissolution of limestone – a glacial erratic block of insoluble rock has served as an umbrella shielding the limestone underneath from solution for the past 14,000 years or so. The limestone plinth is about 30 cm in height, i.e. the local dissolution rate has been ~2 cm per 1000 years. The scene is in the Yorkshire Dales, England.

Karst water gets underground via bedding planes between the individual beds of rock, and joint fractures (usually normal to the bedding planes). Thick to massive beds (30 cm or more, as shown here) support the best karst development.

The Fourth Chute, Bonnechere River, Ontario.

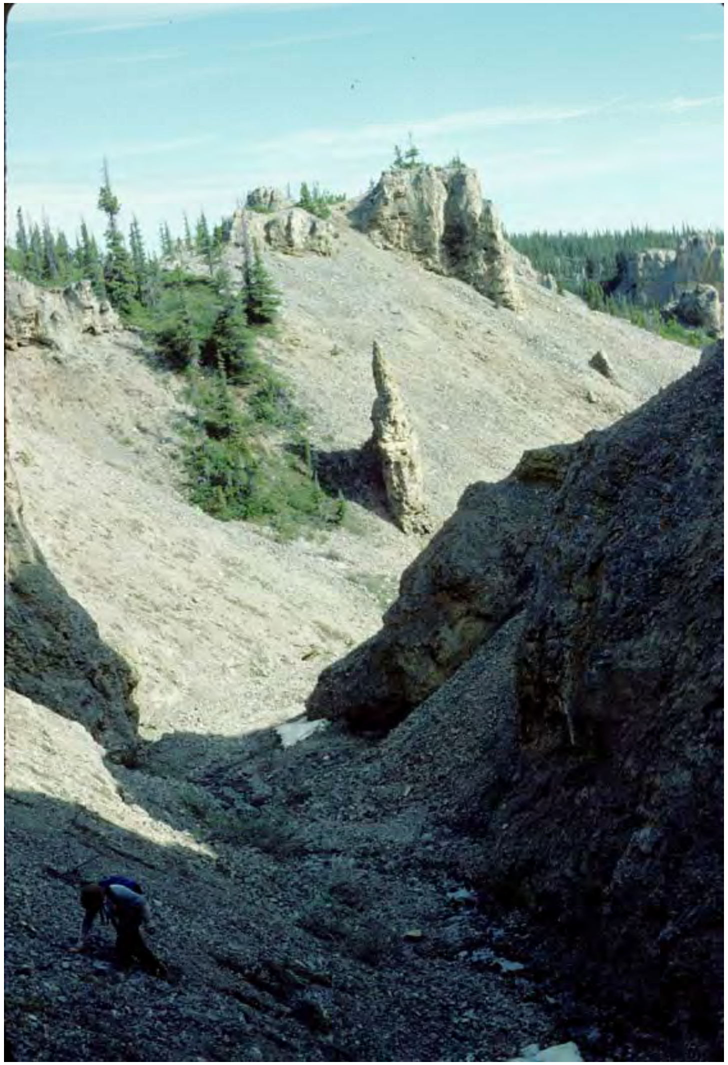
The smallest surface landforms are varieties of solutional pits and troughs, collectively known as “karren”. Together they may cover hundreds of hectares, known as “limestone pavements”. They are especially common where glacial scour periodically scours away surface soil and rubble, so are widespread in Canada.

On left, limestone pavement in Yorkshire, England, displaying effects of soil erosion due to overgrazing.

On right, the magnificent dolomite pavements above Dodo West Canyon, Dodo Creek, NWT.

Deep sub-soil solution isolates karren blocks which may be exposed as ‘pinnacle karst’ if there is later soil erosion; above, at Shilin, China. On right, pinnacles exposed to rain may be sharpened spectacularly; on right, an outcrop in Mulu National Park, Sarawak.

The Shilin and Mulu pinnacle karsts are UNESCO World Heritage sites.



Pinnacle topography is well developed on outcrops of the Bear Rock breccia around Norman Wells. The scenes here are from the Bear Rock itself.

Sinkholes ('dolines' in Europe) are the diagnostic karst landforms. One basic type is the solutional funnel shape, seen here in gypsum in Nova Scotia and limestone in Slovenia (above) and at the Dodo Karst below.

8

Swallowed whole

The driver of this concrete mixer had a rude jolt yesterday morning in Winnipeg when the street collapsed beneath him — swallowing his truck. It took two cranes and two large tow trucks nearly five hours to extricate the truck from the residential street hole. There were no injuries and the cause of the collapse was a large sinkhole forming under the washed-out pavement.

Collapse sinkholes are the other basic type, formed by failure of a cave roof or of a soil arch over buried pavement karst.
<u>Above</u> – soil collapses over dolomite in Winnipeg and gypsum in Newfoundland.
<u>On right</u> – Winter Park Collapse, Fla. This developed in 30 minutes, destroying a swimming pool and swallowing two Porsches.

<u>Left</u> – the Vermillion Creek Collapse, in shaly limestones over gypsum South of Norman Wells, is Canada's entry for the title 'World's Sexiest Sinkhole'. It is a magnificent example of the form at its most pleasing.

<u>Right</u> – there are some hundreds of collapse sinkholes in thin dolomites over gypsum in Wood Buffalo Park.

Incipient collapses can be recognised by the stressed vegetation.

Dry valleys and gorges are larger karst landforms, occurring where an entrenching river is progressively swallowed underground via sinkholes.

<u>Above</u> – a dry valley in limestone under shale cover rocks, W. Virginia.

<u>Right</u> – Rochfort Gorge, France.

Dry valleys are well developed around Norman Wells.

On left – in Mt Kindle dolomites upstream of Dodo Canyon.

Below – in the Bear Rock dolomites in the main Dodo karst.

"Poljes" (corrosion plains fed and drained by water from caves) are the second type of large scale karst landforms.

<u>Left</u> – a 'textbook' example in China.

<u>Below</u> – Third Polje, Nahanni Karst, before and after heavy rains.

<u>Left</u> – Depression No. 142 (van Everdingen, 1981) is an excellent example of a true turlough in a veneer of glacial drift on dolomites south of the Hare Indian River.

A "turlough" (a term from the glaciated landscapes of western Ireland) is a large depression that was created by glacial action such as placement of a barrier moraine ridge but that has drainage underground via karst sinkholes In the spring thaw or exceptional summer rains a true turlough fills or partly fills because its sinkholes cannot discharge all flow immediately. In karst terrains disturbed by glaciations, such as those around Norman Wells, a full range of conditions may be seen, from lakes having surface drainage out at all times, through partly drained lakes to true turloughs, and finally to turloughs where solution has enlarged the sinkholes enough to swallow all flow so that they never flood today.

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‘Moraine Polje’ is a fine example of a moraine-dammed valley that quickly developed underground drainage to circumvent the dam. The lake in it is present every summer but may drain dry in winter. Corrosion around the lake edges is beginning to widen the floor into a corrosion plain, so it is correctly defined as a turlough that is developing features of a ‘classical’ polje. This view is from the top of the moraine barrier. It is on the north bank of the Keele River.

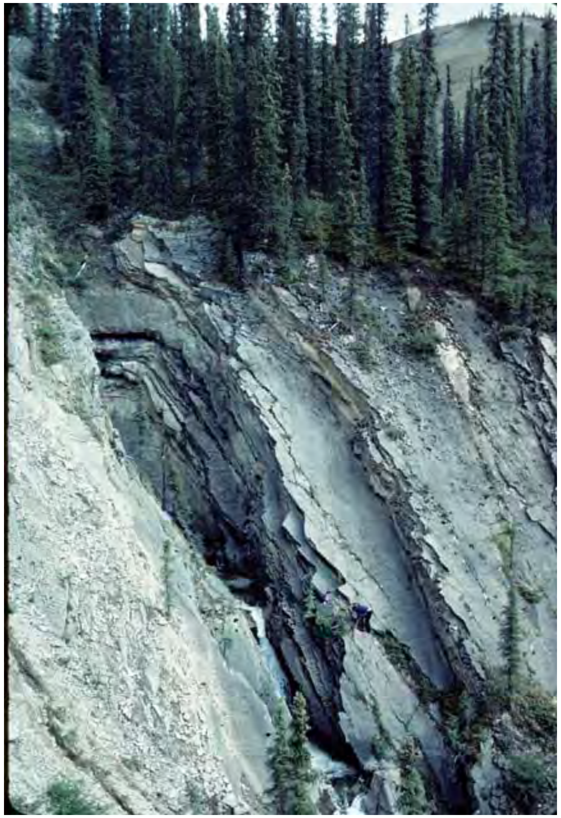
The ‘ultimate’ karst topography is “tower karst”, seen on left on the Li River, China. It is formed by coalescence of deep solution sinkhole formation and corrosion plain action at the water table.

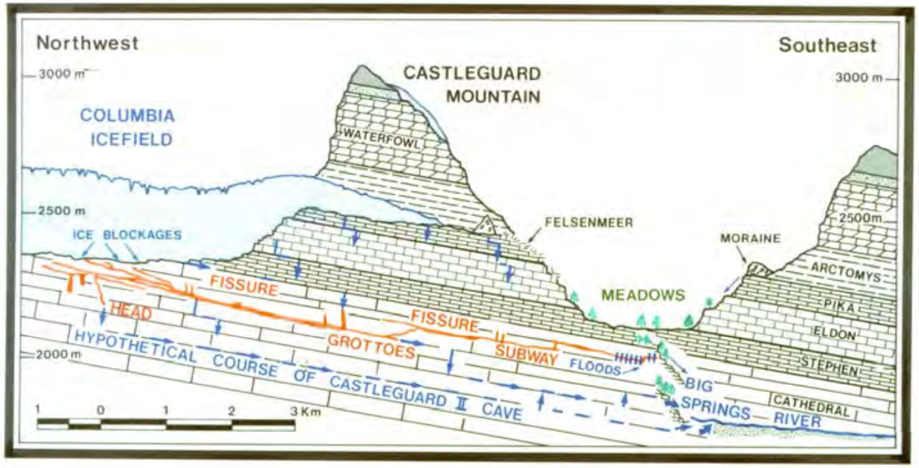
Below left – it appears at smaller scale in Moraine Polje, while the pinnacles in the Bear Rock breccia elsewhere emulate many features of karst towers.

Sinking streams are a feature of karst terrain. In the Castleguard Karst, Banff Park, and in New Britain – above. In the Hare Indian uplands – below.

Springs are a most important feature of karst. <u>On left</u> – vadose in China, phreatic in Mexico.

<u>Below</u> – an ‘icing’ in the Dodo karst, and the spectacular outlet of Moraine Polje, Keele River.

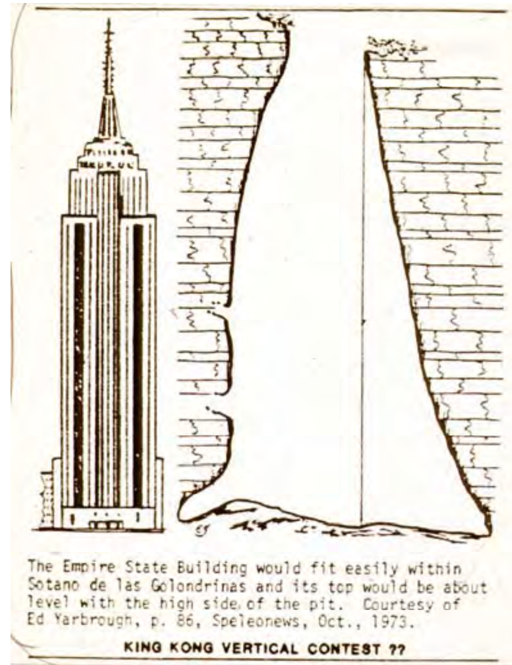




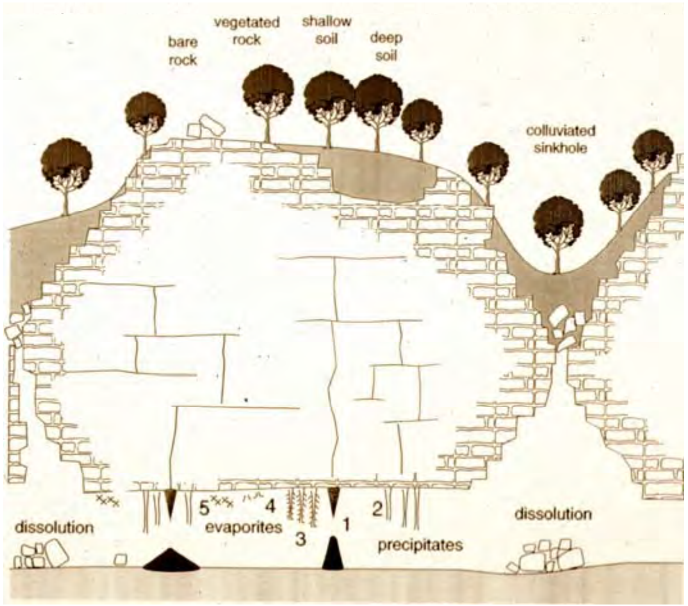
Solutional caves exhibit branchwork (dendritic) or maze plan patterns. Passage cross-sections are 'phreatic' (sub-water table) or 'vadose' (supra-). Phreatic forms are shown here in Castleguard Cave (above and below).

In Gargantua Cave, Crows' Nest Pass.

<u>Above</u> – vadose (gravity entrenchment) and combined passages in Castleguard Cave.
<u>Below</u> – breakdown chambers in Gargantua and in Mexico



Great open shafts created by the combination of dissolution followed by collapse. <u>Above</u> – Sotano de Las Golondrinas, Mexico.
<u>On right</u> – Vermillion Creek, Norman Wells.



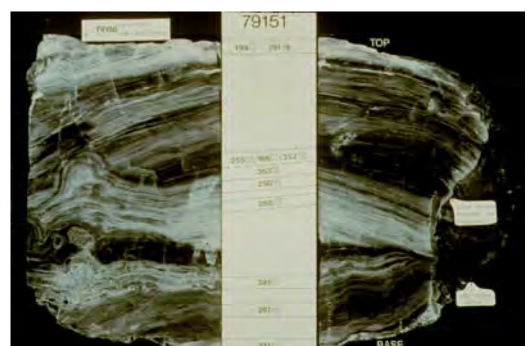
“Speleothems’ are a principal tourist attraction in caves. They are ground water precipitates, chiefly of calcite, aragonite or gypsum. The main forms are stalactites, stalagmites, and flowstones.

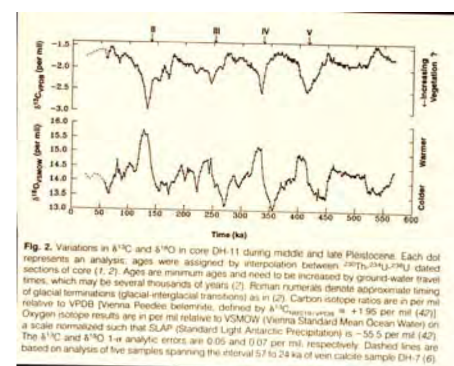
Ice speleothems are common in Canadian caves, exhibiting the standard stalactite, stalagmite, column and flowstone forms. Most are seasonal further south but in the North West Territories many caves longer than a few metres are found to contain blockages of perennial ice.

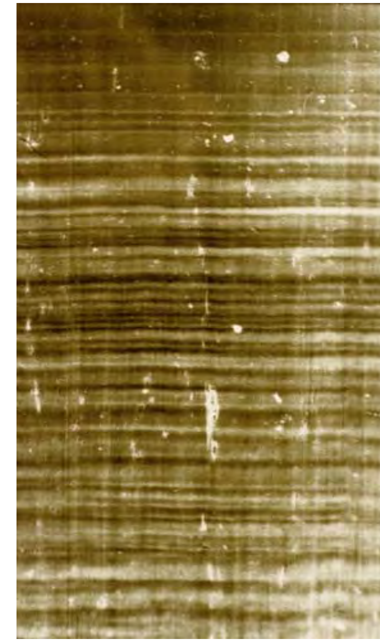
Hexagonal plate crystals of hoarfrost may form in the very stable climates of cave interiors – <u>on right</u> in a cave in the Rockies but we have found them in Nahanni as well.

Solution caves are the longest-lived elements in many landscapes, e.g. above at Crowsnest Pass, where the caves are older than the modern mountain forms.

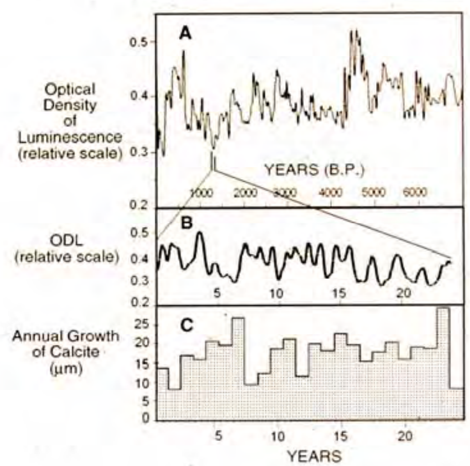
Our research group at McMaster University pioneered dating of speleothems in them to date the caves and paleoenvironmental information that they contain.



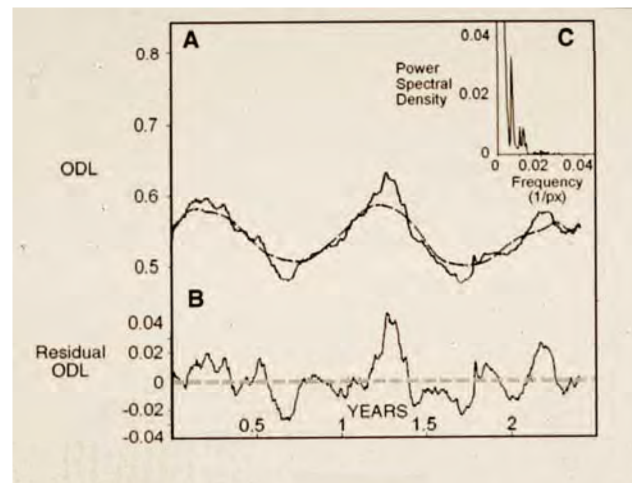




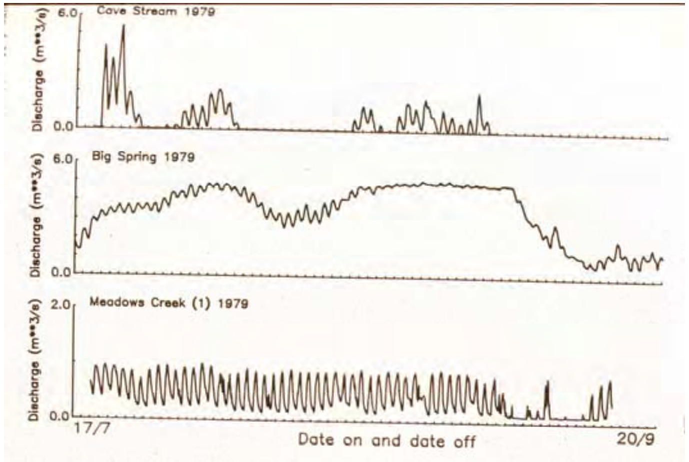
Many stalactites and stalagmites display regular growth bands like tree rings. We have shown that many are annual, recording the seasonal changes in supply of organics such as humic and fulvic acids that become trapped in the accreting calcite. They are being used to study many periodic climatic phenomena such as ENSO and sunspot cycles.

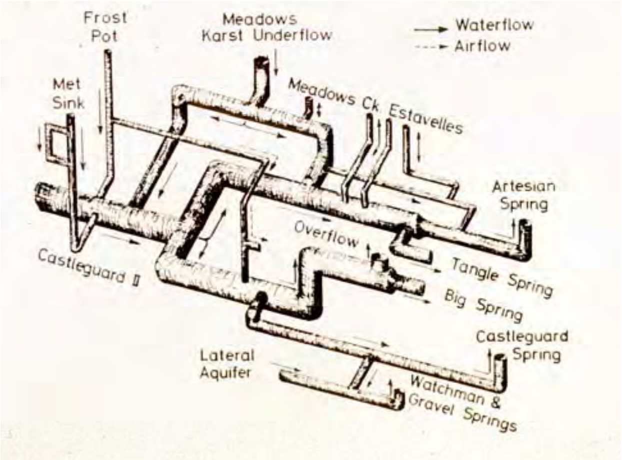


SHOPOV et al Figure 2



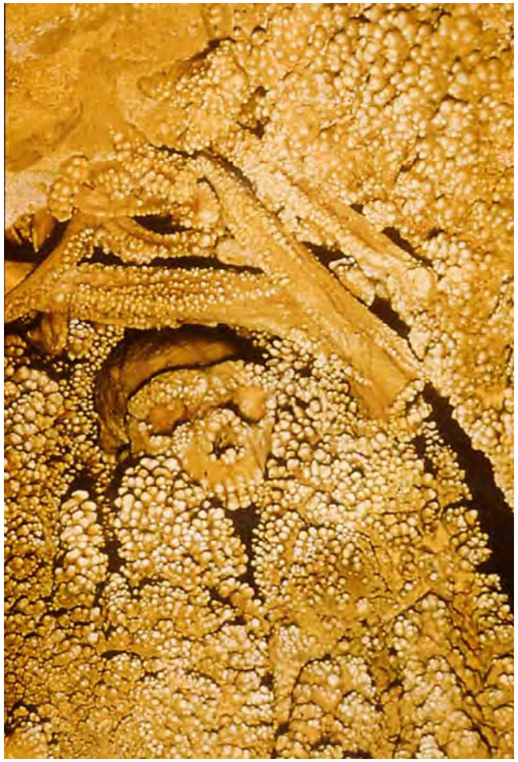
SHOPOV et al Figure 3





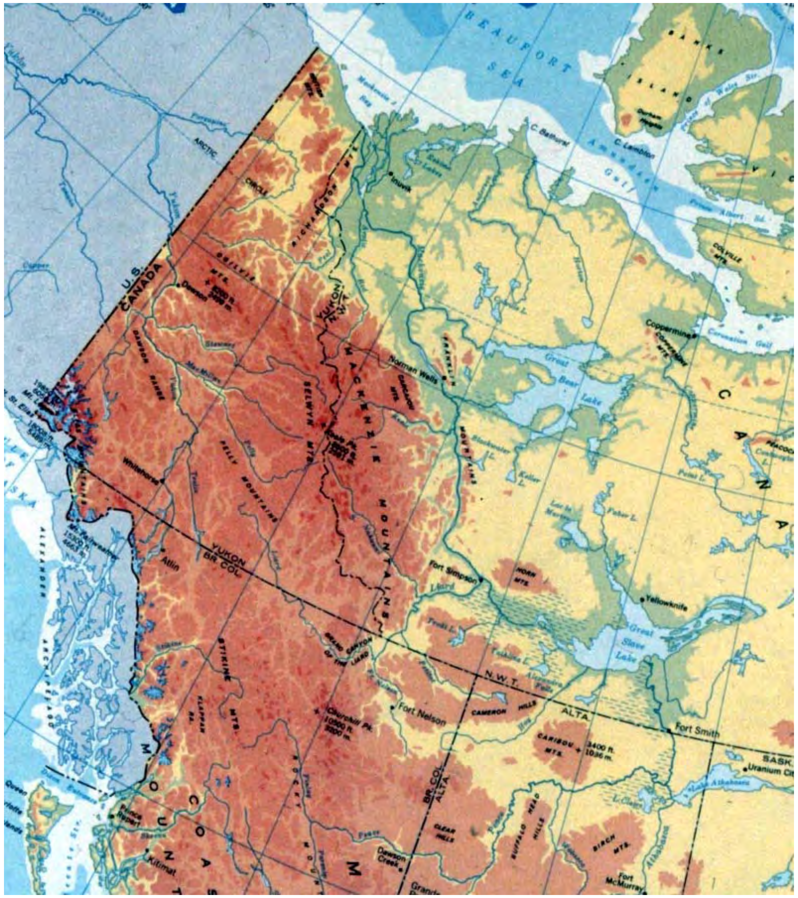
<u>Above</u> – unravelling the form of caves that are inaccessible e.g. Castleguard II.

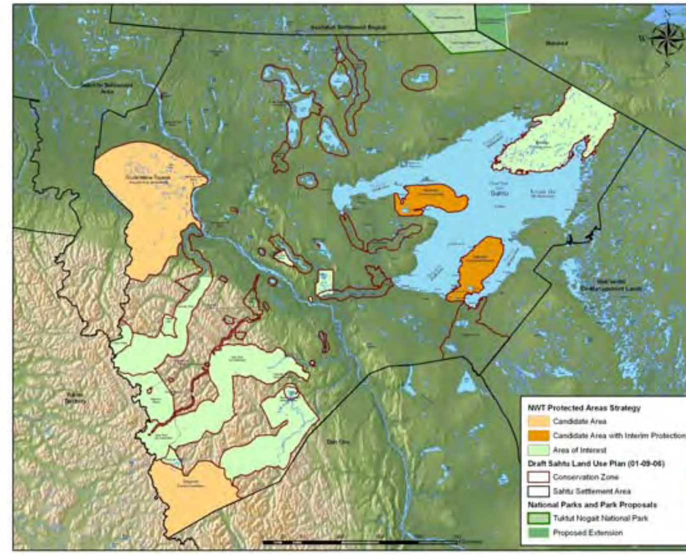
<u>Below</u> – cave painting at Grotte de Niaux, France ~14,000 years BP. *Homo erectus* interment in an Italian cave.



Part 2.

Introduction to the geology and physiography of the study region





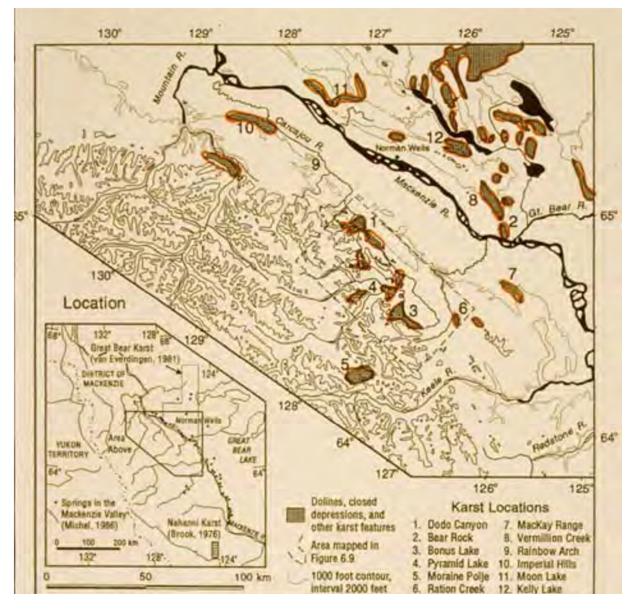


Figure 6.1: Distribution of karst in the northern Franklin and Mackenzie Mountains. The shaded regions are characterized by internal drainage and/or a frequency of dolines and closed depressions greater than $2\ km^{-2}$. Karst data are from aerial photographic interpretation, van Everdingen (1981), and Duk-Rodkin (personal communication, 1990). Also indicated are spring locations sampled by Michel (1986) in a hydrogeological study of the Mackenzie Valley, and the position of the southern Mackenzie Mountain Nahanni Karst (Brook, 1976).

Karst around Norman Wells.

There are at least 14 geographically distinct areas of karst around Norman Wells. Bob van Everdingen (1981) studied six of them in and east of the Franklin Mountains in varying detail. Jim Hamilton (1995) studied five to the west, following a 1981 reconnaissance by Ford.

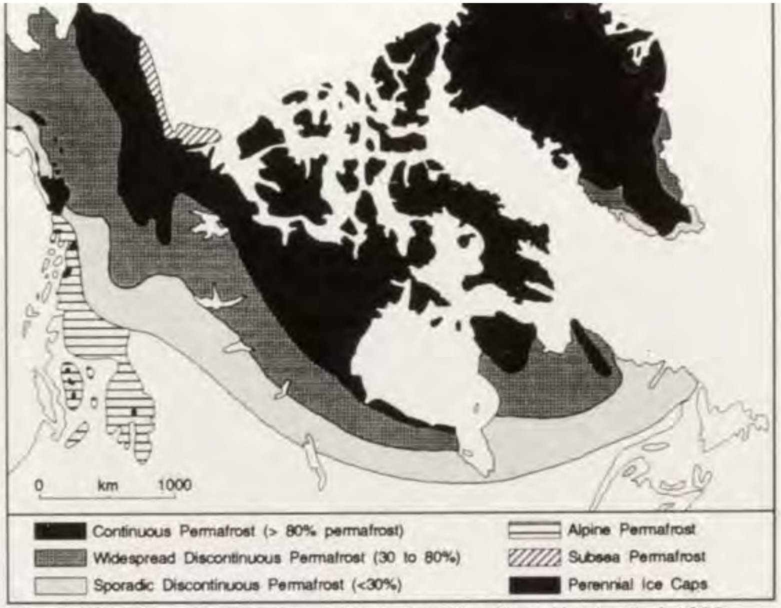
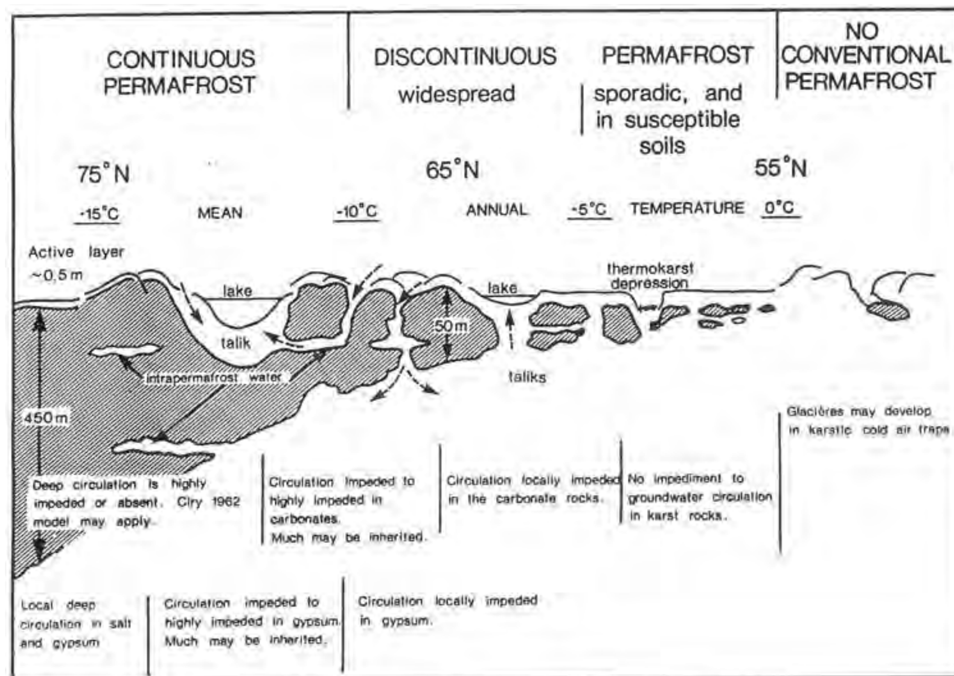


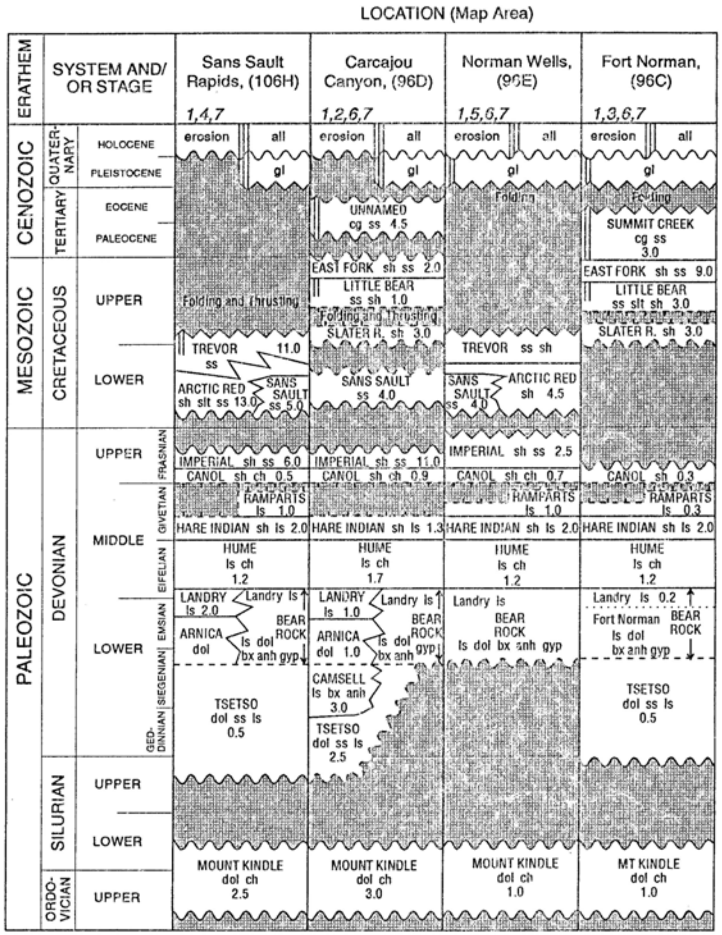
Figure 2.7: Permafrost zones in North America (from Harris *et al*, 1988; after Harris, 1986; Heginbottom, 1984; Johnston, 1981).

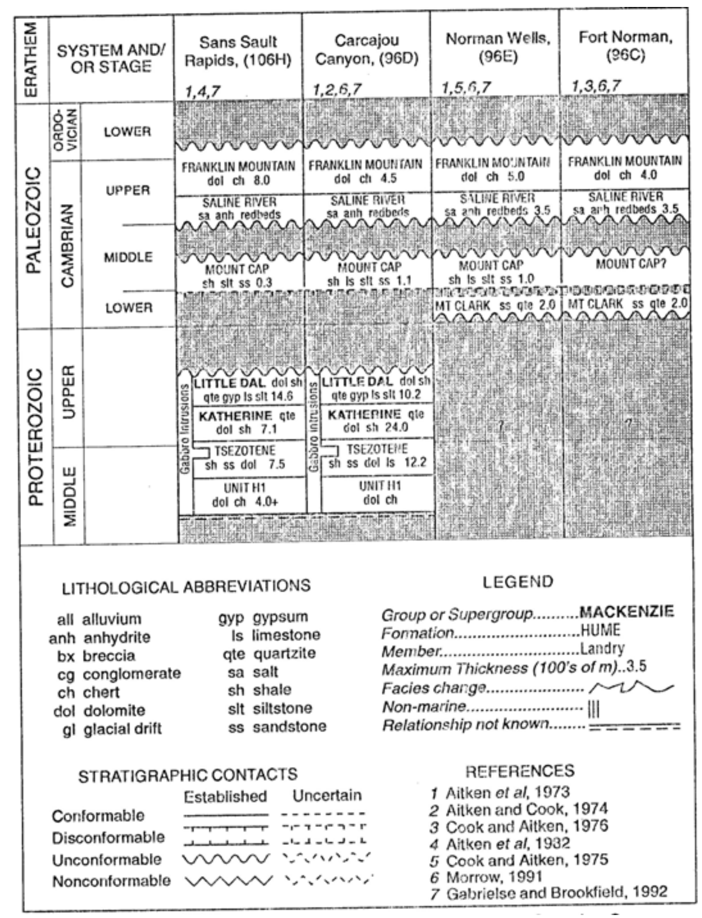
The region straddles the boundary between discontinuous and continuous permafrost conditions, with elevations >250 m being technically continuous. However, the frost is rarely deeper than 50 m or so and will leak (develop 'taliks') where seasonal streams can find sink points in karstic rocks.

On right, Ford's model (1983) for the relationship between permafrost and karst development in Canada. Karst in the less soluble carbonate rocks becomes attenuated North of 68 degrees unless hydraulic gradients are steep and streams are large. There is some karst activity on gypsum and salt North of 75 degrees.



The general stratigraphic section of the region. from van Everdingen 1981





The youngest rocks are at top left and the oldest at bottom right. They are all sedimentary rocks, mostly laid down in successive layers on ancient sea floors. Note that there are big hiatuses in the record of deposition and that not all units (termed "formations") are present at each listed location.

The youngest rocks are unconsolidated deposits of gravels, sands, silts and clays laid down by glaciers, rivers and past lakes during and after the last Quaternary ice age.

The Tertiary, Cretaceous and Upper Devonian strata are all consolidated clastic (fragmental) rocks such as sandstones, siltstones and shales (clay rocks) that are insoluble and so will not develop karst features. They re also mechanically weak in most places and so do not support big cliffs.

The karst develops in strata of Cambrian to Middle Devonian age. At base, the Saline River Fm is a mixture of salt, anhydrite and red beds (clays). Salt is the most soluble karst rock and so can be attacked by groundwater even deep beneath the surface, generating collapse of overlying rocks upwards. The redbeds are very prominent at the head of Dodo Canyon (above).

The Franklin Mountain and Mt. Kindle Fms are varied dolomites separated by an erosion surface displaying paleokarst (e.g. in Dodo Canyon).

The Bear Rock Fm consists of interbedded anhydrite and dolomite and minor limestone in deep wells but is always a breccia variably cemented by calcite when seen in outcrop. The Hume Fm is a limestone, often brecciated at the base by collapse into Bear Rock karst. Ramparts Fm is a thinner, less pure limestone, separated from the Hume Fm by the Hare Indian Fm, shaly rocks (insoluble) with minor limestone; it blocks any extension of karst groundwater circulation from the Ramparts to the Hume and *vice versa*.

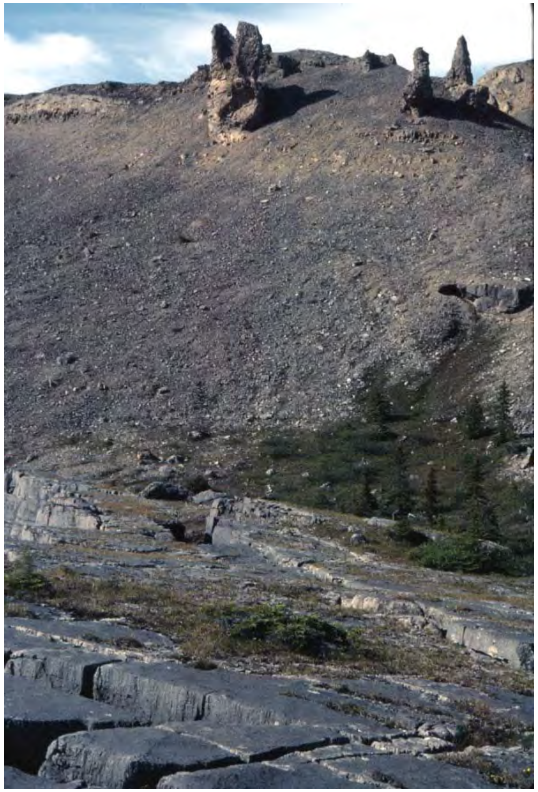
30

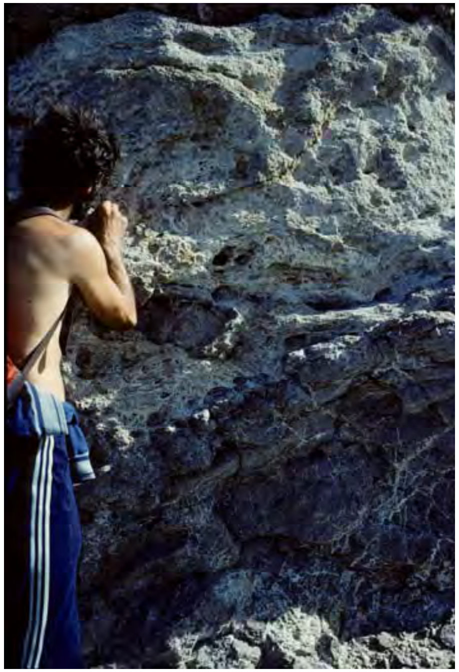
Dolomites are the least soluble of the standard karst rocks. Karst landforms and ground water flow are surprisingly well developed in them in this region, especially given the permafrost climate: e.g. superior to those on the famed Niagara dolomites of Ontario.

Above - The top of the Mt Kindle dolomite at Dodo Canyon. Below – the contact between the Franklin Mountain dolomite (orange) and the Mt Kindle (grey) dolomite in Dodo Canyon.

Both formations are ‘cyclic’ – contain sequences of thicker and thinner beds, the thicker being stronger. East of Norman Wells the Franklin Fm is divided into three ‘members’ – the lowest member (Of2) is impure, the top member (Of4) has prominent nodules of chert (flint – insoluble)

The Bear Rock Formation is one of the two most remarkable solution breccias I have seen (the other is in Belize). Deep beneath Norman Wells cores reveal that it consists of sequences of beds of dolomite and gypsum. Nearer the surface the much more soluble gypsum is progressively dissolved, collapsing the dolomite above into broken fragments, termed 'breccia'. The breccia is now re-cemented by calcite precipitated from the circulating ground waters. The strength of cementation varies considerably, so the Formation displays very variable responses to solution and other erosion processes. Locally, a layer a few metres thick is particularly strongly cemented – the 'Landry Member' seen in the lower photo here.





<u>Above</u> – the contact between the Mt Kindle dolomite and Bear Rock breccia is usually sharp.

<u>Below</u>- details of the Bear Rock breccia, a very remarkable formation.

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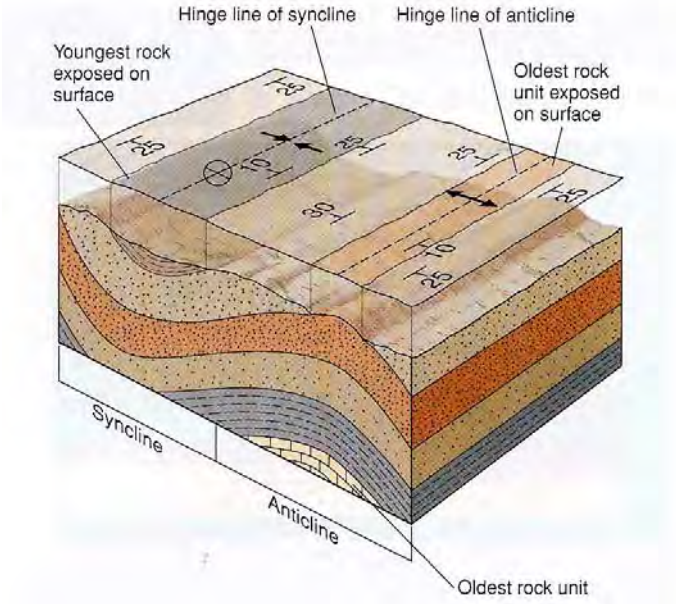
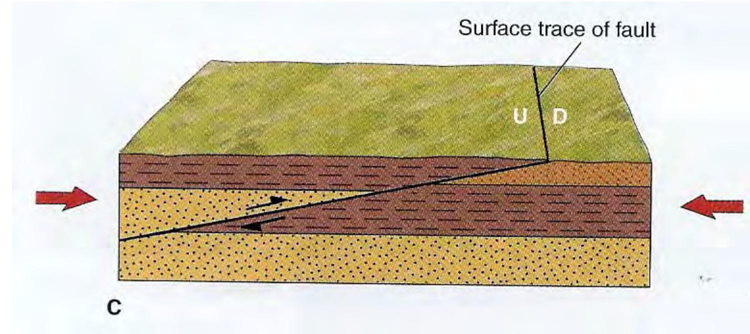
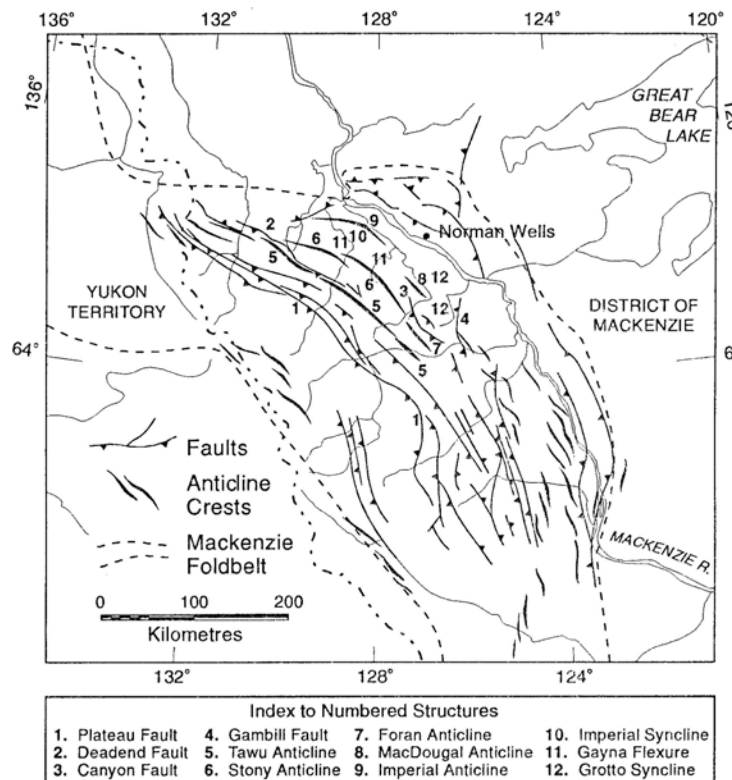
<u>Above</u> – the rugged, chaotic karst topography on the Bear Rock breccia in the foreground contrasts with the regular cliff line of the Hume limestone formation seen behind it. Bear Rock itself is in the far background.

<u>Right</u> – the Hume Formation is a more conventional, regularly bedded platformal limestone that takes good glacial scour and polish.





In some parts of the study region the sedimentary strata remain horizontal and little disturbed although they have been uplifted thousands of metres from their burial positions. But in the Canyon Ranges and the Norman Range they display tilting or anticlinal and synclinal folding (above). Most important is the overthrusting (above right) by force from the west. On right the surface fault traces of the many thrusts. Thrusting is usually accompanied by some folding of the displaced strata.

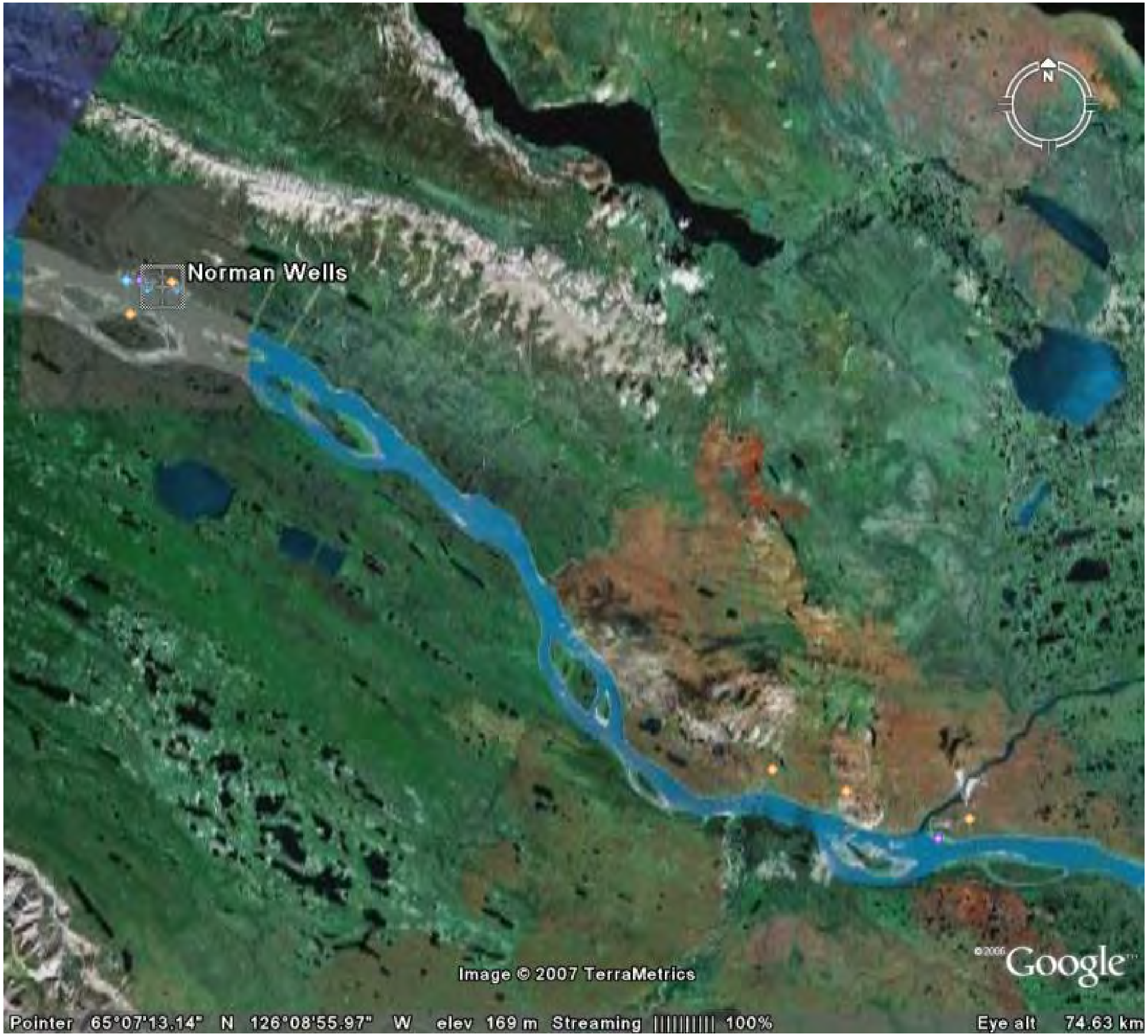


35 **Karst landforms and ground water systems are created by bedrock dissolution. Karst dissolution patterns of behaviour can be very varied in both space and time. Studies during the 2007 visit were limited to basics, measuring the water temperature and specific electrical conductivity (SpC) at each stop. SpC gauges the solute content of a water sample. Broadly – SpC < 120 indicates a water that has not contacted karst rocks to any significant extent. SpC between 120-500 signifies chiefly limestone or dolomite in solution. SpC of 500-2000 = probably mostly gypsum is dissolved. SpC >2000-2500 usually means that there are significant amounts of dissolved salt in the water. Measurements were made with a Fisher Scientific Accumet meter, shown here.**

Part 3 – The karst terrains east of the Mackenzie River

Study Region A. The Norman Range from Norman Wells to Bear Rock plus the eastern foot slopes and plateaus to Bracket Lake

Area A



This Google Earth image shows the Norman Range between Norman Wells and Kelly Lake (to North), extending down to Bear Rock and the mouth of the Great Bear River (southeast). The circular lake on the eastern boundary is Bracket Lake.

The Norman Range is formed by an eastwards overthrusting of the carbonate rocks, chiefly the Franklin Mountain dolomites. Overall, this creates an escarpment landform with a steep 'scarp' face on the east side and a longer, gentler 'dip' slope on the west side. Bear Rock, Hume, Hare Indian and Ramparts strata outcrop on the dip slope. The Mt Kindle dolomites are absent in the Range.

The differing erodibility of these formations, plus multiple overthrusts, has created lesser escarpments on both the main scarp and dip slopes.

<u>Above</u>. The eastern, scarp face of the Norman Range viewed from NE across Kelly Lake.

<u>Right.</u> A view down the dip slope towards the Mackenzie River on an afternoon when the air is thick with smoke from forest fires.

All parts of the Norman Range were overriden by glacier ice of the Laurentide Continental Ice Sheet flowing from the east and northeast.

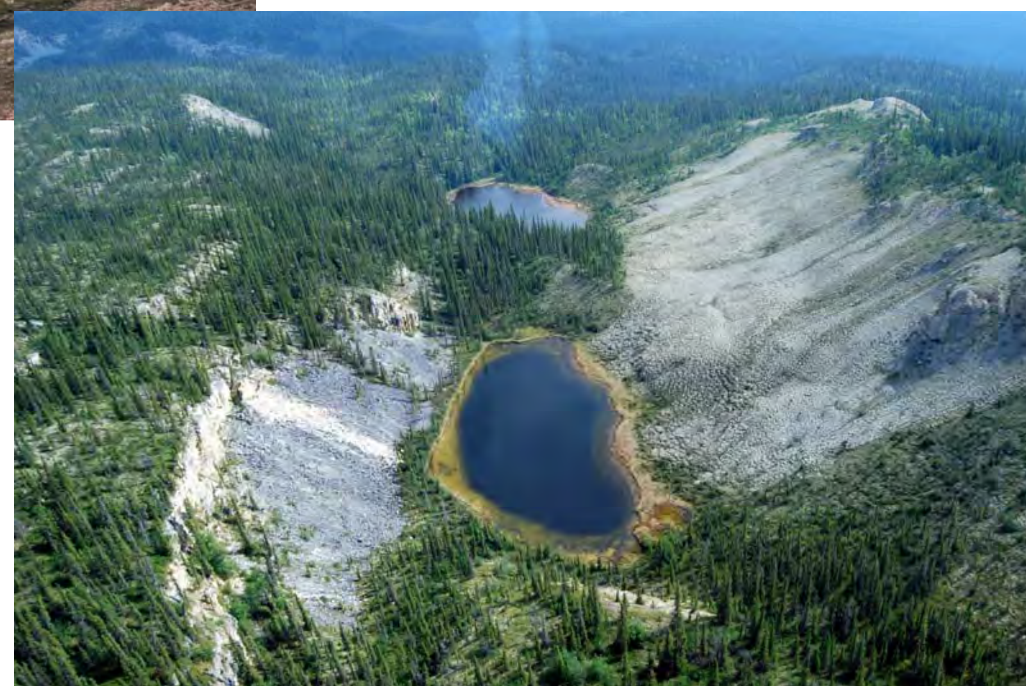
Effects of glacial scour of the rocks are best seen along the crest of the Range, shown here. Strata are the Franklin Mountain dolomites

Most of the glacial 'till' (broken rock debris plastered down under flowing or stagnant ice) that was deposited on the surface of the Range has been washed away by later snow melt and rain water. Only the larger rocks that cannot be moved by shallow water flow remain as a 'lag' on some upper slopes, as shown above.
The two blocks shown in close up on the right are somewhat rounded, suggesting that they were dragged for substantial distances by flowing ice. The red and black lichens growing on them will not grow on carbonate substrates, indicating that these are true 'erratic blocks' i.e. they have been carried from their geological source into a different geologic region. In this case they probably come from Canadian Shield rocks on the shore of Great Bear Lake, at least 100 km distant.

Karst landforms on the strongly ice-scoured upper slopes are composite features, topographically closed depressions created partly by water sinking underground and dissolving the rock along its course, and partly by basal glacier scour. Such 'glaciokarstic' landforms pose a chicken and egg problem. Do glaciers enlarge earlier sinkholes, or do groundwaters adapt prior ice scour depressions?
Shown above are two superb examples that may overflow seasonally but are drained perenially down dip into bedding plane micro-caves in the rock.

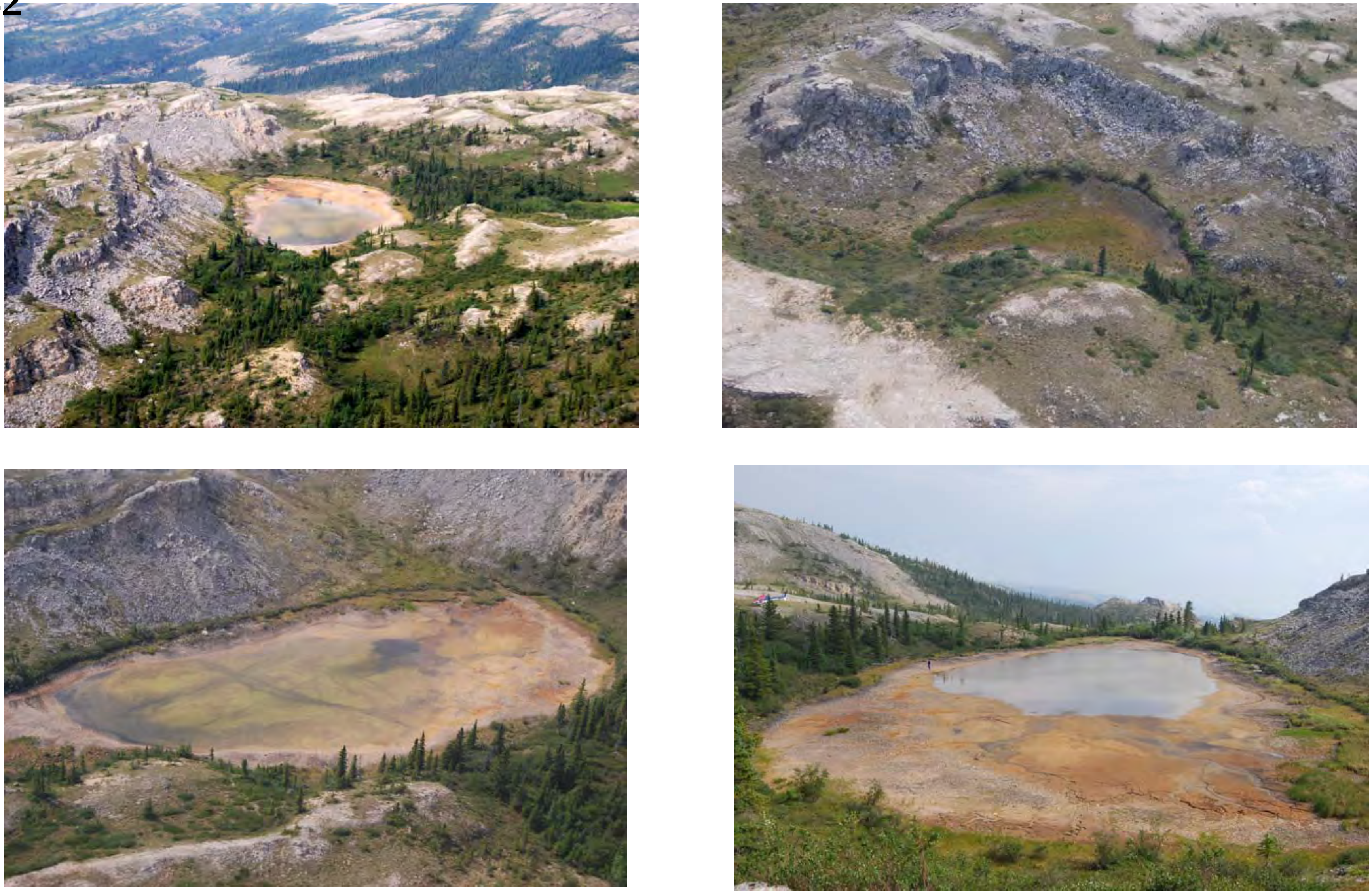
Lower down on both scarp and dip slopes ice scour was often less intensive.

Larger closed depressions that are now drained karstically are common.



The scarp face depression (<u>above</u>) is developed on a thrust plane in the Franklin Mountain dolomites.

The dip slope feature (<u>right</u>) is at the contact between Hume limestone (cliffs to the left) and Bear Rock breccia (eroding slopes on the right).



Stop 1, July 30 2007 . Examples of glaciokarstic sinkholes on the upper dip slope of the Norman Range. Location is 65 23.175 N, 126 52.651 W, at 2240 ' asl. The pool water was at 18.5 C and SpC = 160.5 on a sunny afternoon in a static, evaporating pond.

Central sections of the Norman Range around 65 15'N, 126 10' W, become broader and more rounded in the basal Of2 dolomites of the Franklin Formation. These include thinner beds and some shales and so are mechanically weaker (<u>on right</u>).
Karst sinkholes are less frequent.

More views of the softer terrain on the Of2 member.
The bright red depresssion at bottom right in the upper photo suggests that there may be some outcropping of Saline River shales here.

These pictures show examples of very shallow depressions, some with ponds, in the veneers of glacial drift. Some appear to be drained karstically but detailed field study would be needed to confirm this. Note that patterned ground is well developed in many patches of the drift.

A landing was made by this pair of (probably) karstic ponds at Lat 65 12.98’N, 126 03.05’W. The elevation is 2550’ asl. Note the lobate flows in glacial till in the left foreground.
Lower right – there are many substantial herds of musk oxen grazing in this area.

This major line of lakes is located in a strike-aligned trough in an overthrust in the scarp face of the Range at 65 7.5’N, 125 49’W. Elevation is ~1100 ‘ above sea level. Van Everdingen maps these lakes as drained underground. The two in the foreground certainly occupy topographically closed depressions.

In the southeastern foothills of the Range a closed depression occupied by Yakeleva Lake is a fine example of a turlough at a young stage of development such that it retains a (probably) permanent, shallow lake. All drainage is into the sinkhole seen in the upper right quarter of the photo. The feature is in the Of4 cherty Franklin dolomites.

Yakeleva Turlough is located at 65 10.185 N, 125 42.486 W. Elevation = 1400' asl.
The feature is in the Of4 cherty dolomites.
The floor is of flood clays on glacial till. Most erratics noted were small, angular clasts of Hume-type limestone. There were very few true, well-rounded erratics from further away (i.e. from the Shield around Great Bear Lake). The sinking stream was flowing at 1-2 l/s during our visit. Water temperature was 21 C, SpC = 198. Karst processes are very active in the channel, as shown by fresh collapses 1-2 m in diameter along it.

East of Bracket Lake and Kelly Lake two low plateaus on the Franklin dolomites display widely scattered, very shallow depressions that are probably drained karstically. Many have ponds (above).The line of three small dry holes (right) are suffosion sinkholes created by the down wash of glacial deposits into an underlying cave; that on the left has a fresh collapse in it.

This very shallow depression east of Bracket Lake drains underground into the small sinkhole seen as a separate small pond on the right.

The southern end of the Franklin Range includes Bear Rock itself (centre above), similar mountains to the north of it, Vermillion Creek Sinkhole (under cloud), and the confluence of the Great Bear River.

Vermillion Creek Collapse Sinkhole

Photo by R. van Everdingen.

Vermillion Creek Sinkhole is located at 65 08.217 N, 126 05.5 W. Its rim is at an elevation of approximately 270 m (900 feet) above sea level. It measures 120 x 60 m in plan view and is about 40 m deep to the waterline.

The top of the collapse is through shales and shaly limestones of the Canol Fm, with limestones of the upper Ramparts Fm probably being seen in the lower half of the cliffs. This collapse will have been triggered by dissolution of gypsum in the Bear Rock Fm below, or by dissolution of salt in the Saline River Fm, or by both.

The world's shapeliest karst collapse sinkholes are either cylindrical, or elongated along a vertical fracture to create an ellipse such as is seen here. The walls are vertical. Vermillion Creek Sinkhole is the finest example of a fresh collapse that I have seen anywhere in Canada or the United States. <u>It is strongly recommended for protection.</u>

Bear Rock seen from the Mackay Range west of the Mackenzie River

In contrast to the main sector of the Range to the north, in the southern Franklins and Bear Rock itself the Bear Rock Fm (Db) and overlying Hume limestone (Dh) are preserved at the crest line on top of the Franklin Mtn Fm (COf). This forms a series of east-facing, dissected scarplands at lower elevations than in the main Range. This scene is north of Bear Rock, which is in the background left.

There are many shallow closed depressions in the lower hills N of Bear Rock, most of which probably drain karstically.

<u>Above right</u> a scarp face in the Hume Fm is seen to be buckled downwards locally by solutional undermining in the Db breccia beneath it.

<u>On right</u> – a large sinking lake

The massif of Bear Rock viewed from the north across the scarplands. In background right, across the Mackenzie, is the Mackay Range.

The principal topographic and karst features of Bear Rock are shown in this figure from Jim Hamilton's PhD thesis that is based primarily on his careful geologic and karst mapping.

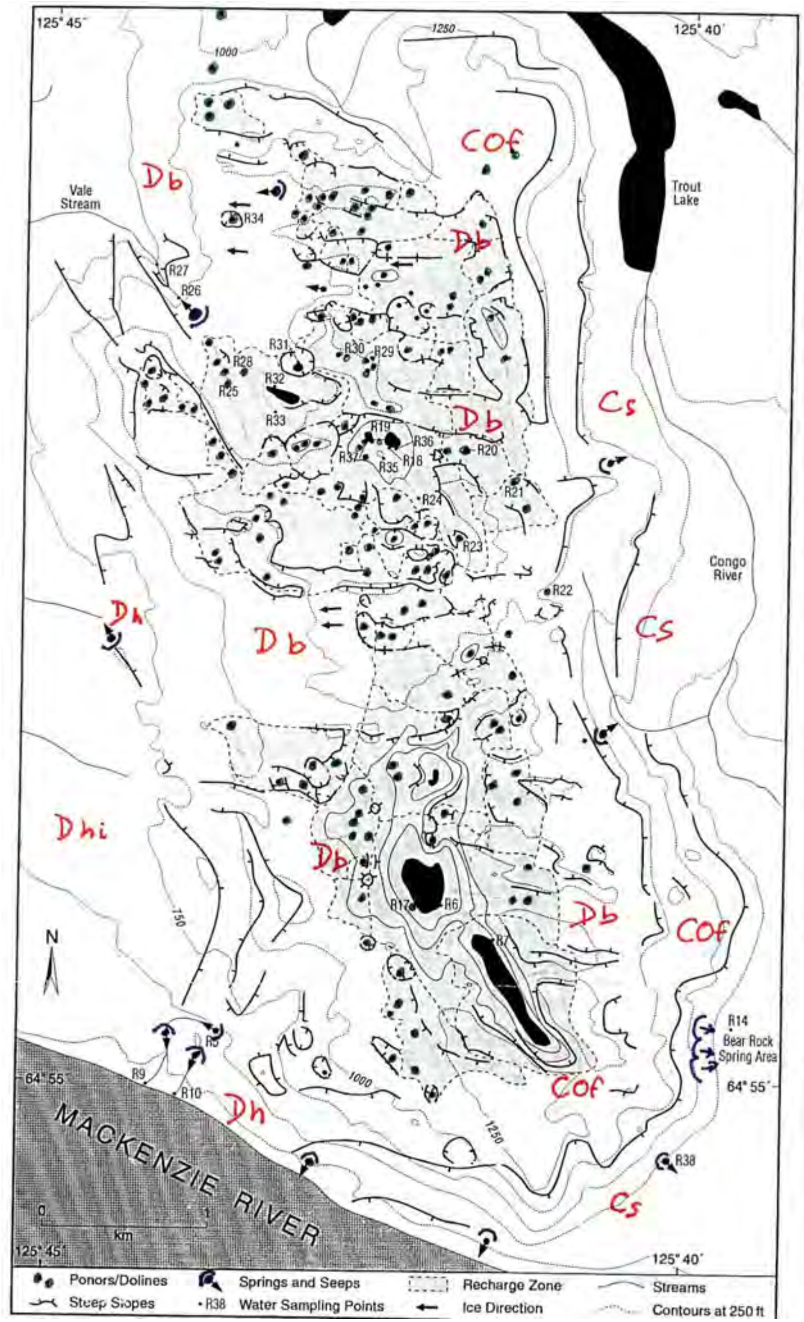
The shaded highland area is the source of most of the karst ground water recharge. It can be divided into two distinct parts, a broader northern half with abundant rock pinnacles and small, steep-sided sinks, and a narrower southern half with two larger lakes, "Long" and "Round" in a major closed depression.

Hatched lines mark the chief E-facing cliffs.

Sinkholes are emphasized in green.

The principal karst springs are emphasized by blue arrows. They are roughly radially distributed around the Rock. The greatest outflows occur in apron-like "Spring Area" in the SE. This discharges throughout the winter, when the emerging waters freeze to form a major icing (Ger. "aufeis").

In red, Cs + outcrop of the Saline River Fm. COf = Franklin Mtn Fm. Db = Bear Rock Fm. Dh =Hume Fm Dhi = Hare Indian Fm.



On northern Bear Rock.

<u>Above</u> –rugged, E-facing scarp in the Franklin Mtn dolomites.
<u>Above right</u>- typical recharge area on the Bear Rock breccia.

<u>Right</u> – one of several prominent pinnacle ridges in the breccia on northern Bear Rock.

In the pinnacle country of northern Bear Rock

Right – a ridge descending towards the River.

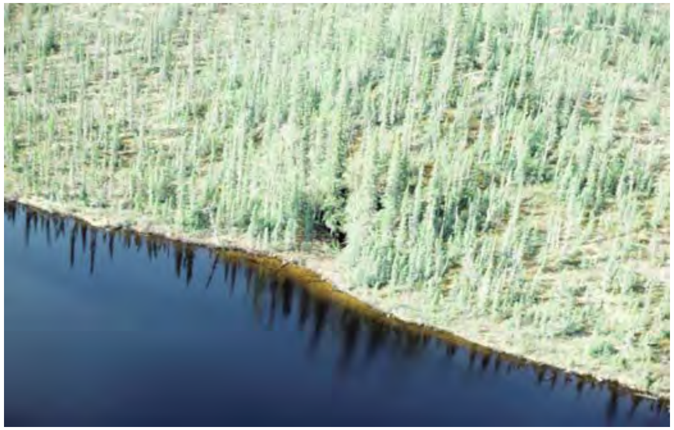
Below – steep dry valleys with fragile pinnacles that somehow endure, and many caves that quickly become impassably small.

Striking solifluction features such as stone stripes and lobate flows in the talus below a pinnacle ridge on northern Bear Rock.

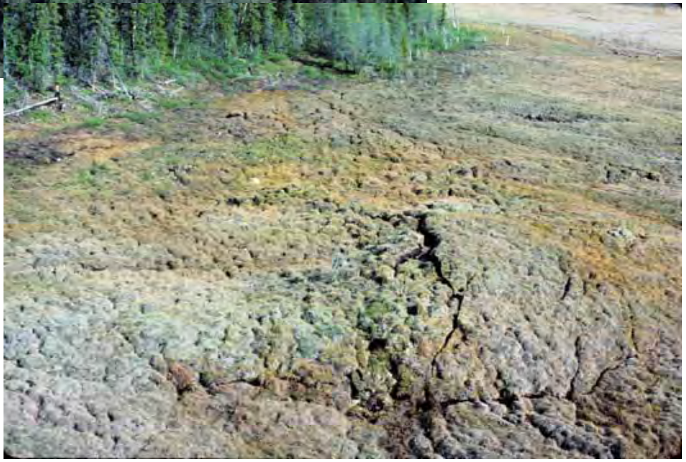
The larger sinkholes occupy glacier- ice-scoured depressions contain small ponds, as shown here.

The crest of southern Bear Rock.
<u>Above</u> – the Long Lake karst depression with the River and Mackay Range behind
<u>Right</u> – Long Lake in rear with Round Lake in the foreground. The two lakes are aligned along a depression scoured in the crest of an anticline with Franklin Mtn dolomite in the floor and Db breccia forming the cliffs.

<u>Above</u> Round Lake with the Mackenzie River in the rear. This view emphasizes the steep hydraulic gradients that exist between ground water sink points on the crest and potential spring points at River level below. Arrow shows the sinkpoint of the lake, into an impassably small cave. Detail at right.



The Bear Rock Springs Area is the prominent tree-less apron seen above. Ground water emerges at many different points (detail on right). Jim Hamilton estimated summer discharge at around 20 litres/second. T =3.7 C. SpC~1400.Total dissolved solids ~1000 mg/l, indicating that there is much dissolved gypsum in the water. There is some discharge throughout the winter.



Bear Rock towers over voyagers on the Mackenzie River. The tributary flow from Great Bear River is easily distinguished at the foot of the Rock.

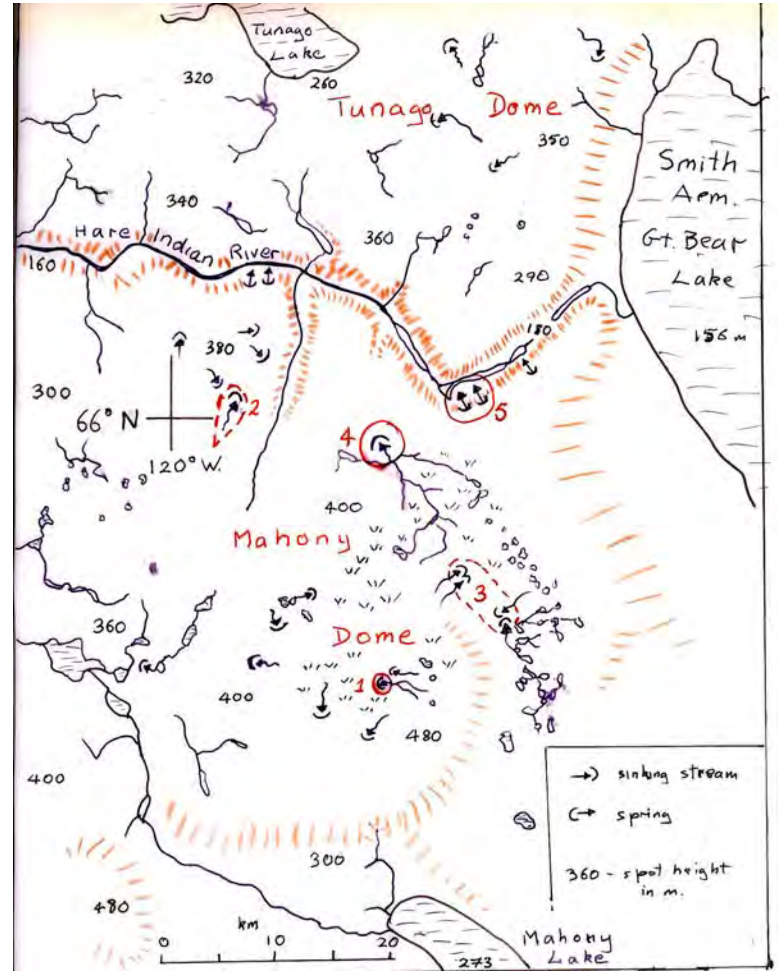
RECOMMENDATION – that the Bear Rock karst area outlined in the map on page 39 be protected as a reserve representative of karst landforms and processes on the Norman Range. While it does not display features typical of karst on dolomites of the Franklin Mtn Fm further north, the latter are too scattered and little known. Bear Rock is very significant for the variety and high density of its karst. It is most important that the reserve be large enough to encompass all of the springs shown on the hydrogeological map.

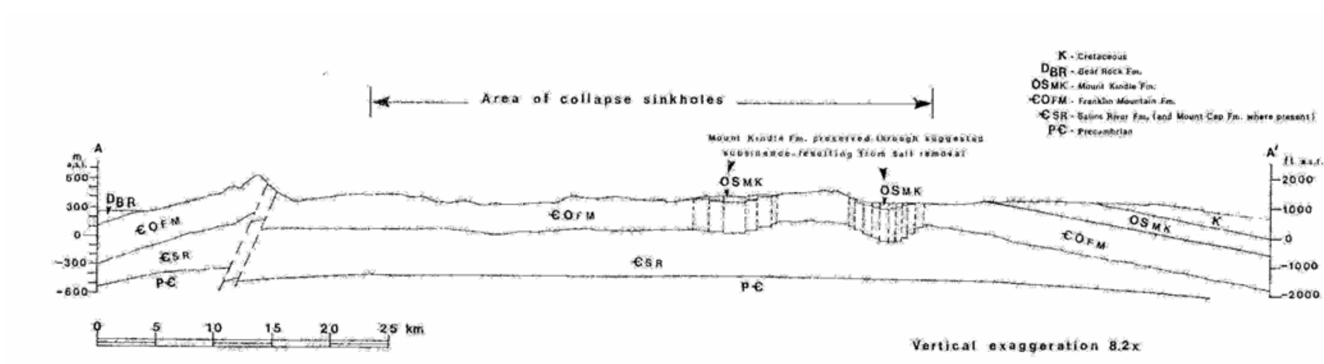
The karst landforms and groundwater patterns of Bear Rock were intensively studied by Dr J.P. Hamilton as part of his PhD thesis. His discussion of Bear Rock is attached as Appendix I to this Report.

Bear Rock is already proposed for protection on cultural and historic grounds. It is hoped here that the addition of a karst component to the protectorate therefore will not cause any significant difficulties.

Study Region B. The Hare Indian eastern plateaus (the Mahony Lake and Tunago Lake 'domes')

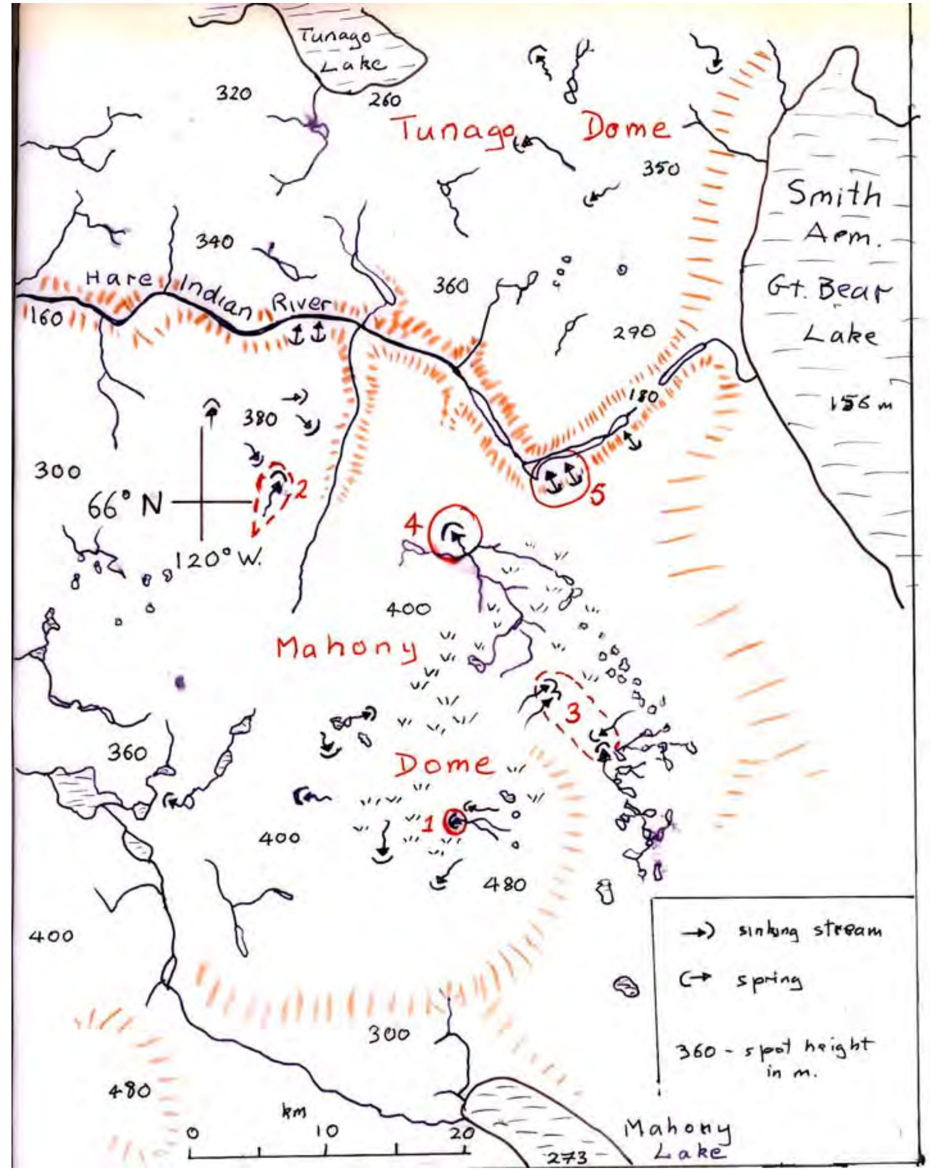
71 **In his 1981 report R. van Everdingen adopted the names, Mahony and Tunago Lake 'domes' for two shallow plateaus east of the Norman Range. The sketch map on right shows their locations. The two separate features have been created by the deep entrenchment of the Hare Indian River Valley, a major glacial spillway.**
Geologically, the region lies east of the zone of intensive thrust faulting and folding that created the Franklin Mountains. As shown in the section below (from Van Everdingen) the bedrocks are the Franklin Mtn dolomites, underlain by the Saline River Fm and with some Mt Kindle Fm dolomite possibly preserved on top in down-dropped areas.



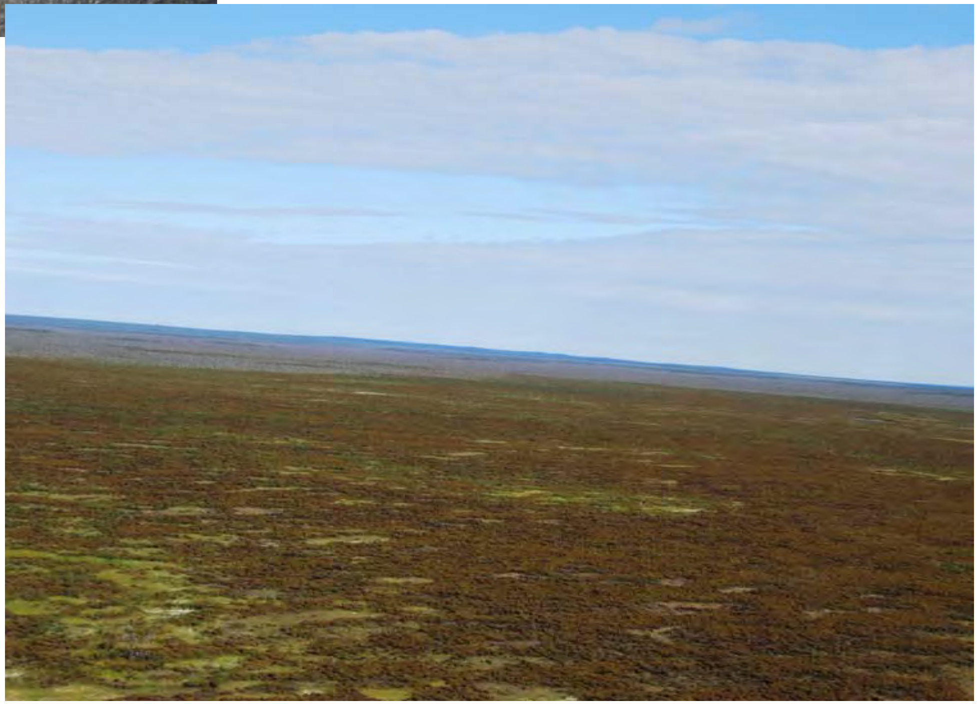


 The two plateaus are gently uplifted to 350-400 m asl or more along their eastern edges overlooking Smith Arm (lake level at 156 m asl) and then tilt down gently westwards at 1-5 m/km. The general flatness of the terrain is emphasized in the frontispiece, page 70. The plateaus display dozens of sinkholes, both glaciokarstic and post-glacial in origin. Mahony Dome has fine turloughs.

Ideally, when a karst rock plateau is uplifted, karst drainage and landforms will develop first around the edges because ground water hydraulic gradients are steepest there, and then extend progressively inwards. Something like this has happened on Mahony Dome, where the edges are now mostly well-drained underground but the centre is still very marshy, with only incipient sinkholes appearing.



Five ground stops were made on karst features of the Mahony Dome in July 2007. They are numbered on the figure and discussed in that sequence in the pages that follow.



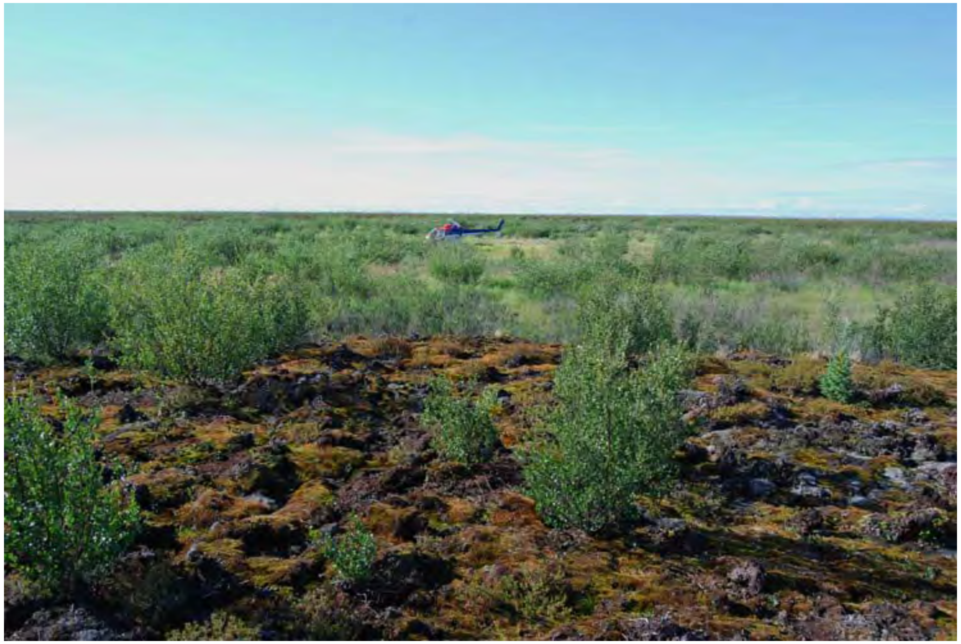
The extreme flatness of the terrain in the centre of Mahony Lake dome is seen in these two low elevation helicopter shots.

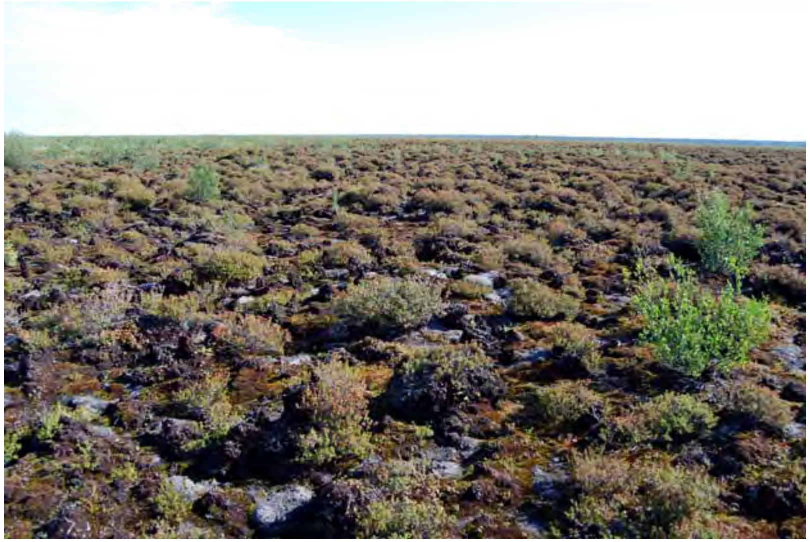
Central Mahony Dome.
In the <u>upper pair of photos</u> water flows out of a wetland pond on glacial deposits and is progressively lost underground in the channel downstream.

<u>Right</u> – glacial tills and other deposits appear to be very thin over much of this terrain, however. Sinkholes that expose bedrock at very shallow depth are common.

Ground Stop #1 was at a very fresh, young (certainly post-glacial) sinkhole close to the centre of Mahony Dome. Location is N 65 47.934’, W 125 36.0’ at an elevation of 430 m asl.

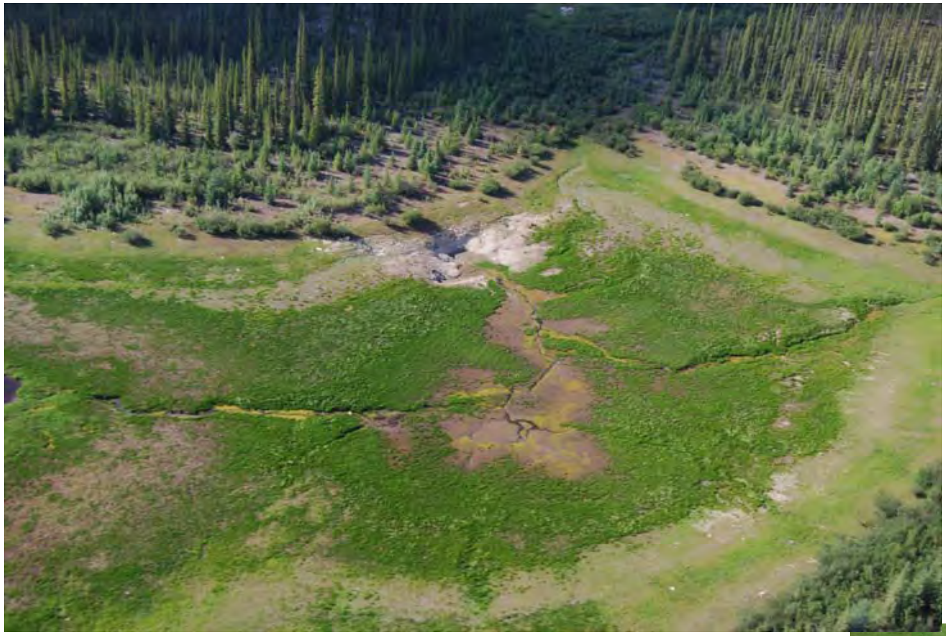
The sinkhole is seen to be a collapse in bedrock under shallow till. There is dessicated peat for a radius of ~100 m around the hole, with fresh peat outside. Karst drainage is progressively drying up a wetland here.






Upper left - dessicated peat around the sinkhole rim. Right –there are one-two metres of stony till above the bedrock. All larger clasts were of local dolomite but there were many small, well-rounded pebbles of Shield origin. Below – the water sinks into medium bedded, fine-grained dolomite.

Ground Stop #2, Mahony Dome. R. van Everdingen's Sinkhole #142. Location – N 66 00.86', W 125 52.86'. Elevation at lowest sinkpoint ~300 m asl. The feature is ~3 km in length, 1.5 km maximum width. It is clear that it has a few permanent ponds and an extensive area subject to frequent flooding. Van Everdingen showed that flooding occurred in the Spring thaw and lasted for a few weeks most years. It is the finest example of a mature turlough I have seen in the entire region.



Turlough #142 has one major downstream sink complex plus several lesser sinks upstream on the flanks of the depression.

These are are two examples of the lesser sinks.

Aerial views of the downstream sinks. There is a main stream into bedrock at left centre in the upper photo, with an overspill pond on the right that drains to a separate sinkhole.
The lower photo shows both sinks and a small permanent pond that is perched on two metres of till above them.

On a warm, sunny evening the temperature of the sinking water was 25 C. The specific conductivity was 306 micro-siemens, suggesting that the water carried a small load of dissolved dolomite, probably from fragments exposed in the glacial till.

<u>Above</u> – the main stream sink in July 2007. It appears very much the same as in a 1977 photo by van Everdingen. The sink is into the cherty member of the Franklin Mountain Fm. A chert nodular mass two metres thick is exposed in a flanking cliff. Such thicknesses are exceptional

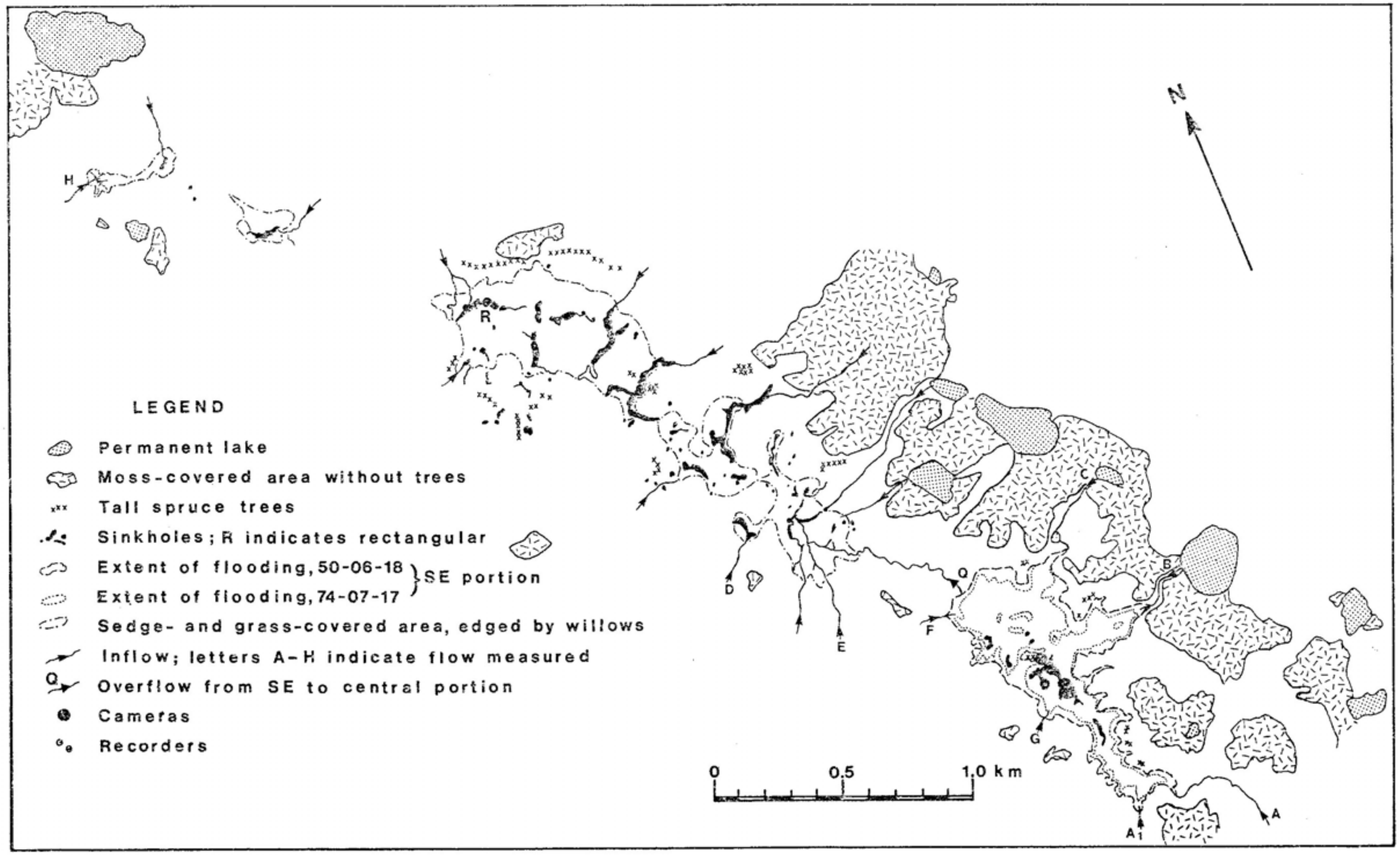
The overflow pond by the main stream sink, Turlough #142. Strand lines from flood water lakes are clearly seen on the banks. On right – the overflow sink. A powerful stream flows into this sink at stages during the rise and fall of the annual flood, as indicated by the size of the limestone blocks and chert cobblestones that it sweeps along.

Turlough # 142, looking upstream from the main sink. This feature floods to the forest trim line in most years. Van Everdingen recorded flooding from mid-May to mid-July in 1977. The maximum volume of water sinking (all sinks combined) was estimated at about three cubic metres per second.

#142 is recommended for protection as an outstanding example of a mature turlough.

Aerial overview of part of Sinkhole #110, a turlough depression in the Old Age stage of its cycle, now drained by many independent karst sinks.

Two more overviews of Turlough #110. <u>Above</u> – shallow sinkholes in the central sector of the depression; the forest is encroaching on ground that rarely floods today. <u>Right</u> – overhead view of a cluster of sinks in the north.



Van Everdingen's map of Sinkhole 110 in 1977. The depression extends for ~6 km from the southeast (or upstream) end to the northwest (downstream). It collects melt water and runoff from all sides but chiefly easterly. In its early days it will have flooded to form a single lake more than 20 square km in area that was drained by only one or two sinkholes. Karst development has been quite rapid so that today it is drained by 40 or more separate sinks of varying size and shape. Local areas still flood annually but much of the depression is desiccated. Shrubs and forest are advancing into it.

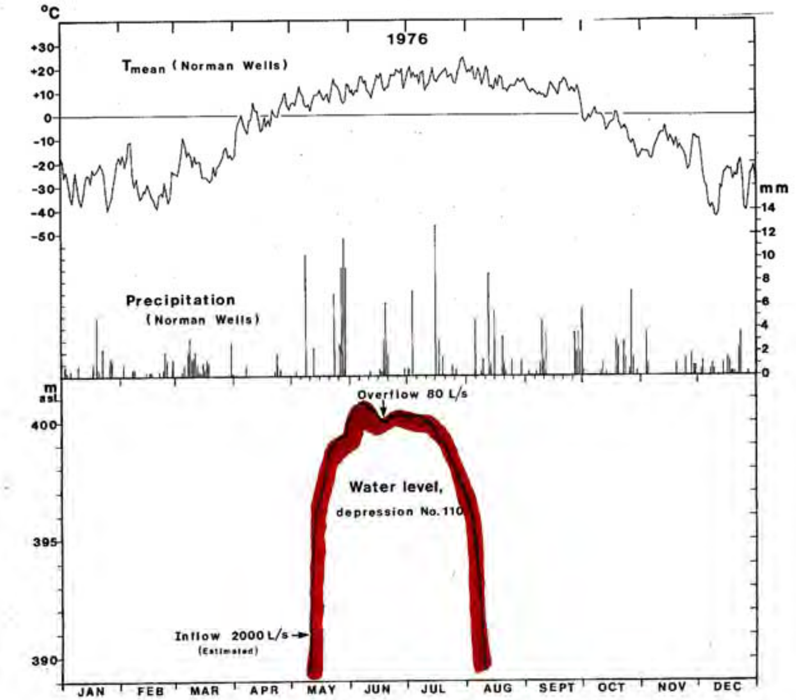


Figure 22. Daily mean temperatures and daily precipitation at Norman Wells Airport for 1976 (data from Atmospheric Environment Service), and water level in the southeastern portion of depression No. 110, recorded by pressure recorders.

van Everdingen studied the southeast sector of the turlough in 1976, when it filled and overflowed northwards into the central sector. The figure above plots air temperatures and precipitation at Norman Wells and shows the duration of the spring thaw-summer flooding that year. (Photos by van Everdingen).

Aerial view of a major upstream (SE) sinkhole where Ground Stop 3(1) was made in 2007. The sink is in the cherty member of the Franklin Mountain Fm. A dry stream channel is seen at bottom right.
Location is N 65 51.07’, W 125 23.27’. Elevation is 370 m above sea level.

The Franklin Mtn dolomite at Stop 3(1) is a clean, fine-grained buff rock with the many 'vugs' (shallow pits) typical of pure dolomites. It is regularly bedded and jointed, presenting many lines of weakness for solutional attack. Solution along some major joints creates a pattern like crumbling city blocks and is described as 'ruiniform'.

There was no water flowing into this sinkhole during our visit on July 31 2007 but the dry channel entering it from the southern end has a bedload of pebbles, cobblestone-sized boulders and larger, all ‘imbricated’ (wedged together and tipped upwards in the downstream direction) that indicates a flood flow of more than one cubic metre per second.

There is a veneer of one-two metres of very stony till around the perimeter of the sinkhole. Note that it is progressively sapped down into bottom as the centre of the sink is approached (above – the piles steadily diminish in size); this is a pretty effect of floodwater that I have not seen anywhere else. Right- the till here consists chiefly of local chert fragments.

Two views of the lowest points in the sinkhole at Ground Stop 3(1). These places are where most water will pass underground during the flood periods. The larger dolomite blocks are toppling into them and disintegrating. There was only grass or damp mud in the bottoms, suggesting that the sinkhole had flooded briefly in 2007, presumably during the spring thaw.

There is a line of larger, quite spectacular, individual sinkholes towards the northern end of Turlough #110. Ground Stop 3(2) was made in open ground 200 metres south of them at the location - N 65 51.65'; W 125 24.53'. The elevation of the rims of the sinkholes was ~370 metres above sea level.

Further aerial views of the northern sinks at Ground Stop 3(2). It is seen that around the rims the ground is dry and in process of being colonised by shrubs. The sinks themselves flood frequently (every spring time?) but the inter-sink flats between them now appear to have escaped flooding for a period of at least several years.

As one walks northwards at Ground Stop 3(2) the sinks become progressively deeper. <u>Above</u> – a dry stream bed enters the shallowest. The water moves chert boulders when in flood. <u>Right</u> – sinks 3-5 metres deep.

The southerly large sinkhole at Ground Stop 3(2). It is about ten metres deep. Dissolution first segregates large blocks along vertical joint faces. The blocks then topple into the sink and disintegrate along bedding planes.

The central large sinkhole at Ground Stop 3(2).

The northerly large sinkhole at Ground Stop 3(2) is a dramatically narrow shaft that appears to be younger than the others but is now evolving rapidly.

<u>Recommendation</u> – that Sinkhole #110 of van Everdingen (1981) be recognised and conserved as an outstanding example of a glaciokarst turlough in the Old Age stage of development when what was once a single spring thaw lake is disintegrated and largely desiccated by drainage into many younger sinkholes.

Ground Stop #4 – “The Disappearing River” of van Everdingen (1981). The location is N 65 58.76’, W 125 35.64’. Elevation of the rim of the sinkhole is 332 metres above sea level. The river sinks into van Everdingen’s Sink 86B, with occasional overspill via a meandering channel into Sink 86A in the foreground.

A second aerial view of the Disappearing River, looking northeast. The overspill Sink, 86A, is in the foreground. The River sinks at the NE end of the central sink and there is a smaller collapse sink behind it along the same joint fracture trend. Beyond it is a permanent pond. Muskeg in the foreground and rear appears to be suffering some desiccation, probably due to the development of karst drainage.

On our visit on July 31 2007 the River was flowing at an estimated 10 l/second and occupying only 30% of its channel. In flood it transports rocks up to small boulder size. The water was dark brown and peaty in colour, from the muskeg. Temperature was 19.9 C and the Spc was only 42 microsiemens, indicating acidic water with plenty of capacity to dissolve the dolomite downstream.

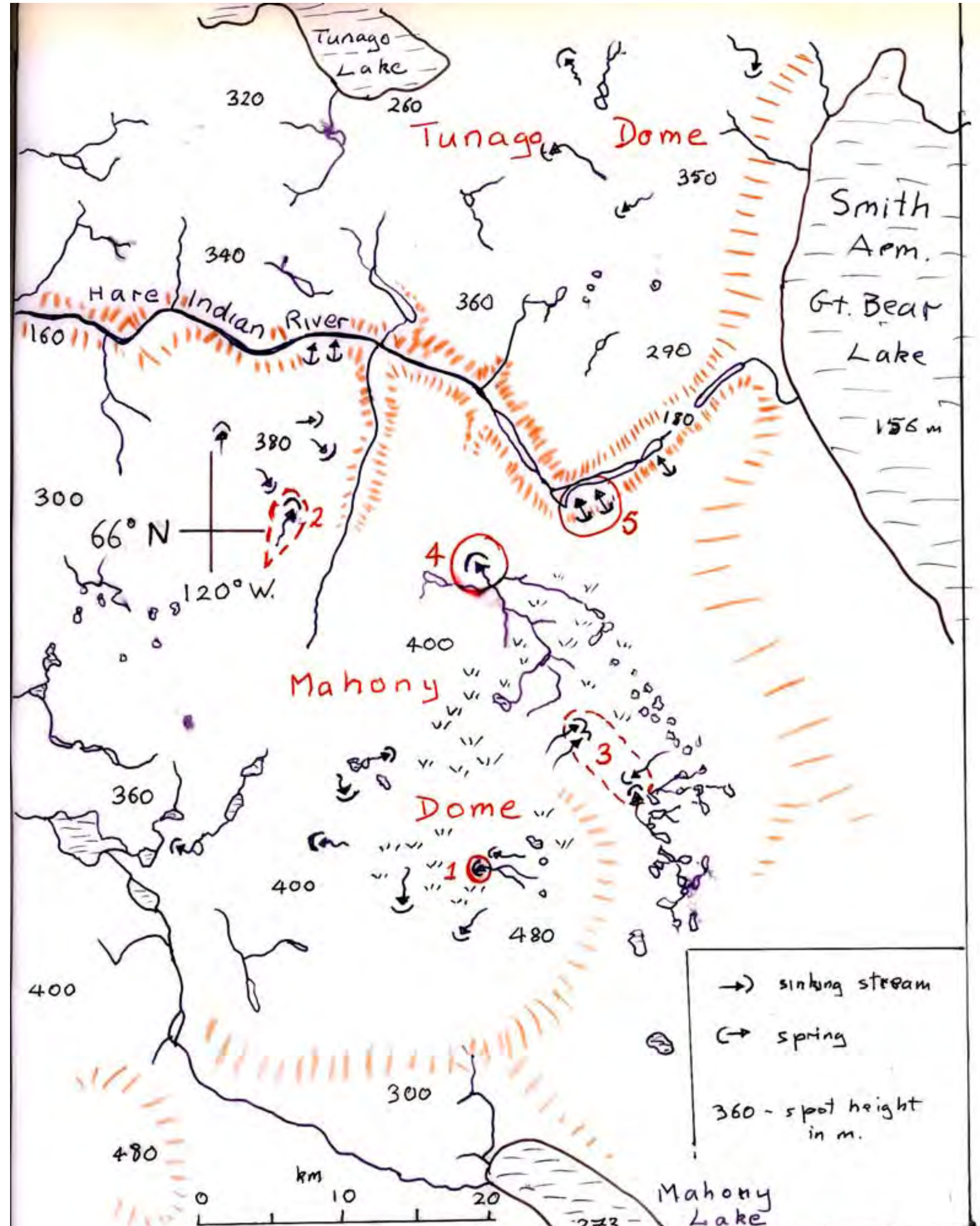
The principal sinkhole, #86B, is approximately 100 m in length, 40 m wide and 25-30 m deep from the rim to the water sink.

Entering it, the River first drops down a small waterfall (<u>above</u>) and then builds a detrital fan (<u>right</u>) out into the depression.

The River sinks underground through a pile of fallen dolomite blocks at the NE end of Sinkhole # 86B. A large chert mass is seen in the cliff on the right, indicating that the bedrock here is the upper, cherty unit of the Franklin Mountain Fm.

The Disappearing River of the Mahony Dome karst is one of the two finest examples of sinking rivers I have seen in Canada, and the finest that is in dolomite. The other, the sink of the Salmon River on Anticosti Island, Quebec, is in more soluble, pure limestone.

<u>Recommendation</u> – that the Disappearing River line of sinkholes be protected as a foremost morphological example of stream sinks in dolomite. Comprehensive protection here would encompass the watersheds of both the Disappearing River and the Old Age Turlough (#110), which most probably lies upstream of it in the pattern of karst ground water drainage here.



The Hare Indian River Valley

The valley is a glacial spillway formed by melt waters pouring out of the Laurentide continental ice sheet over Smith Arm. In its eastern parts the valley is a straight-walled entrenchment into the dolomites, 120-150 m deep and 1200-1500 m wide. Its nearly flat floor is an infilling of glacial and proglacial sediments. In the eastern sector these pond up a series of elongated, shallow lakes, shown above looking east towards Smith Arm, Great Bear Lake.

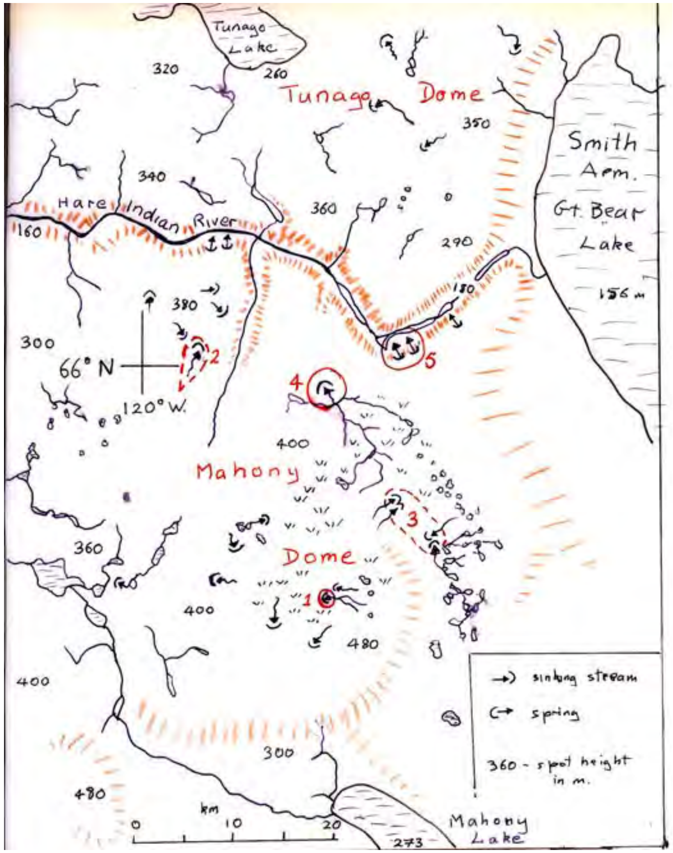
Two further general views of the valley. <u>On left</u> – the lakes at its head, with Smith Arm in the background. An eastern cluster of karst springs emerges at the foot of the dolomite bluff in the centre of the picture.

<u>Right</u> – the valley west (downstream) of the lakes, looking east. van Everdingen (1981) mapped an icing (freeze-up of perennial springs) over the shoaling River channel in the foreground and a western cluster of springs (Nos. 149 and 150) at the foot of the slopes on right behind it.

Location of spring #144 was N 66 0.86’, W 125 26.98’. Elevation was 165 m above sea level.

Van Everdingen (1981) mapped three groups of springs in the Valley. The central group (Nos. 143-5) were the largest and are shown above emerging from the southern wall. Ground Stop #5 was made on the principal stream (on right, #144, viewed upstream and downstream). The Volume of flow on 31 July 2007 was ~1.0 - 1.5 cubic metres per second (or 100-150 times greater than the flow in the Disappearing River that day). Water temperature was 4.1 C. The specific conductivity was 390 microsiemens, suggesting a dissolved load of dolomite of about 150 mg/l.

Aerial views of the eastern group of springs. No ground stops were made here. The water is typically peaty and probably similar to that of Spring #144 in temperature and SpC.



Van Everdingen reported no springs on the north side of the Valley. It appears that most Groundwater comes from the karst lands on the Mahony Dome to the south. These are the finest example of karst drainage on glaciated dolomite plateaus known anywhere. Probable underground drainage connections are suggested on the map.

A provisional areal plan for protection of the best representative sample of the Mahony Lake Dome karsts is indicated by the dashed line boundaries drawn on the map above. The plan integrates the Old Age Turlough, the Disappearing River and the principal Hare Indian springs into one natural reserve and places the Mature Turlough in a second reserve. The plan requires a modest program of ground water dye tracing to confirm that the hydrologic connections are as suggested.

Recommendation – that the two karst reserves drawn above be adopted if/when the hydrologic catchment boundaries are confirmed.

109 Karst features on the Tunago Lake Dome

A view northwest across the Dome, with Tunago Lake in the background.

Tunago Lake Dome is underlain by the same horizontally bedded dolomites of the Franklin Mountain Fm as on the Mahony Lake Dome. North of it to the shores of Lac des Bois (N 66 45') it is replaced by Mt Kindle dolomites (also horizontal), a few small outcrops of the Bear Rock Breccia, and Cretaceous shales: the terrain becomes even less rugged.

R.O. van Everdingen mapped >200 topographically closed depressions on the Tunago Dome and north of it, including three large turloughs (Depressions 181, 182, 183). There are also many sinking streams and springs. Most individual karst landforms are not as distinctive as on the Mahony Lake dome and it appears that the patterns of underground karst drainage are not as well organised, probably because of greater degrees of interference by past glacial action.

On the Tunago Lake dome there are patches of rectilinear corridor terrain reminiscent of the Nahanni karst but much shallower. This suggests that, in contrast to the Mahony Lake dome, this area experienced sub-glacial mega-flood erosion which disrupted the earlier patterns of karst drainage. The deeper sinkholes are scattered widely apart, draining into local cliffs, as seen in these pictures and the upper one on page 110.

<u>Above right</u> –a further illustration of the scattered nature of closed depressions on this dome. <u>Right</u> – two views of a small turlough that is drained into the dolomite cliff behind it.

<u>Conclusion</u> – karst features seen on the Tunago Lake dome are less striking than those of its neighbour and are not proposed for reserves at this time.

Study Region C. Lac Belot and its underground river, Lac Belot Ridge, Tunago Ridge and the Belot Karst.

Lac Belot Ridge, looking south. The southern end of Lac Belot is seen to the left.

In his study of the karst east of Norman Wells, R.O van Everdingen did not explore the features around Lac Belot although he surveyed this far to the north when visiting Lac des Bois further east. As a consequence I did not attempt any detailed aerial survey or ground landings in the Lac Belot region during the 2007 study visit. This is now seen to have been a serious oversight.

There are few published reports on the area. A geological map with accompanying notes was compiled by J.D.Aitken and D.G.Cook (1969) as Map 6-1969 Geology - Lac Belot, Geological Survey of Canada: Cook and Aitken further commented on some remarkable tectonic features of Lac Belot Ridge and Tunago Lake Ridge in Memoir 19 of the American Association of Petroleum Geologists, 1973, pages 13-22.

Before leaving Norman Wells on August 4 2007 I visited the Wildlife Management, (Sahtu Region) offices of the Department of Environment and Natural Resources to view maps and other work under preparation there, and was able to discuss many matters with Mr Richard Popko, Wildlife Technician. It was noted that the Draft Sahtu Land Use Plan dated 01-09-06 lists a "Colville Lake Traditional Conservation Zone" that includes Lac Belot, and a separate but adjoining small conservation zone south of it labelled "Underground River" that begins at Lac Belot Ridge and ends on the Hare Indian River. Documentation on a legend of the underground river is given on page 115.

Bedrock in the zone is the Bear Rock Breccia Fm. The topographic maps show some very large, potentially significant, closed depressions. Unfortunately, resolution of the Google Earth images here is not good enough for analysis. <u>This is considered to be a key area for survey in a future visit because it is most likely that it is a very significant karst whose features will support the conservation proposals of the Sahtu Draft Plan.</u>

Site Description

As told by an elder from Fort Good Hope, this story from an ancient time describes how the people from the Colville area found the people from the Good Hope area:

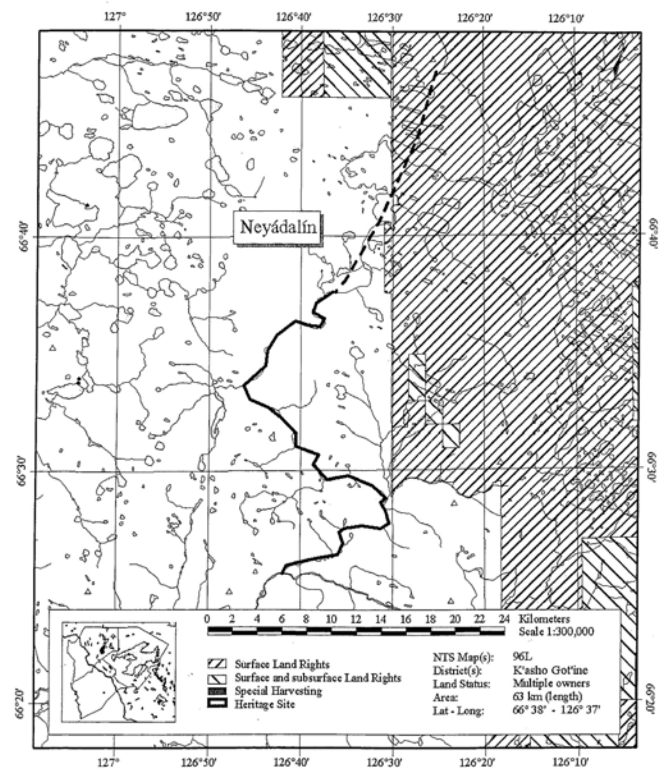
I'll tell you the story Neyádalín*—the river that runs underground and how two brothers went through it. There was once a Dene that always lived alone with his family. He made his living at* Odarah Tué *[near Bellot Lake]. People would say that he lived alone with his family because he was jealous of his wife. He had two grown sons that were old enough to take wives. But how could they since they were always alone? One day the brothers were hunting ducks along the shores of the lake. They each had their own canoe, and they were chasing a goose with two chicks. They were very close to them when the goose ran ashore with one chick. The other kept going and the brothers continued to chase it. The chick went into a creek then suddenly disappeared. The older brother was wondering what happened to the chick when suddenly he too went underground in that creek! His younger brother also went underground. The creek became very swift as the older brother shot through it. As he went thrashing around in the underground creek he came upon a giant pike. He went into his mouth and passed right through it. Next he came upon a giant Loche that he also passed through. On and on he went until he saw a small light. He yelled out in joy because he thought he might have a slight chance of surviving. Then suddenly he came shooting out from the side of a cliff where the creek was gushing out. His whole canoe flew in the air, and then landed on* Xaıstá Nılı̨né *[Hare Indian River]. He was waiting there hoping that his younger brother would show up, when suddenly he came shooting out of the cliff. The older brother said, "So this is the reason why when I was coming to my mother before I was born, I saw flying canoes that carried me into her."*

It was a good thing these boys were able to handle things with their medicine. This was a strange land for the two boys because they have never gone further south from where they were raised at Odarah Tué*. They paddled along the Hare Indian River until they could see signs of people. They talked about the signs and wondered if they would be able to understand their language. They paddled on and on until they suddenly came out into the* Dasho Ho *[Mackenzie River]. They had never seen such a big muddy river before. They stopped on the shore and noticed smoke rising from* Koıgojeré Du *[Manitou Island; p. 52]. They crossed the river and found that the people spoke the same language. They were very thankful but they weren't feeling good because they had been underground. They had medicine in their bodies so they weren't feeling good. They decided that they were going to go to the Ramparts. There they went through the cliffs. These are the two lines that run through the cliffs that can still be seen today. These are the marks that these two brothers left. After they did this they felt much better and they lived with people in the Good Hope area for two years.*

They both took wives and probably even had children when they decided to return to their parents who were still searching the shores of Nılı̨n Tué *[Belot Lake] with a raft. The parents had been searching the shores of that great big lake and had given them up for dead, when one day they saw two canoes coming to their camp. They waited on the shore and the family was overjoyed to see one another. Their family lived with other groups from then on. It is said that this is how the groups from around Colville area became aware of the people who lived further south. This is a very ancient story.*

Recommendations for Protection

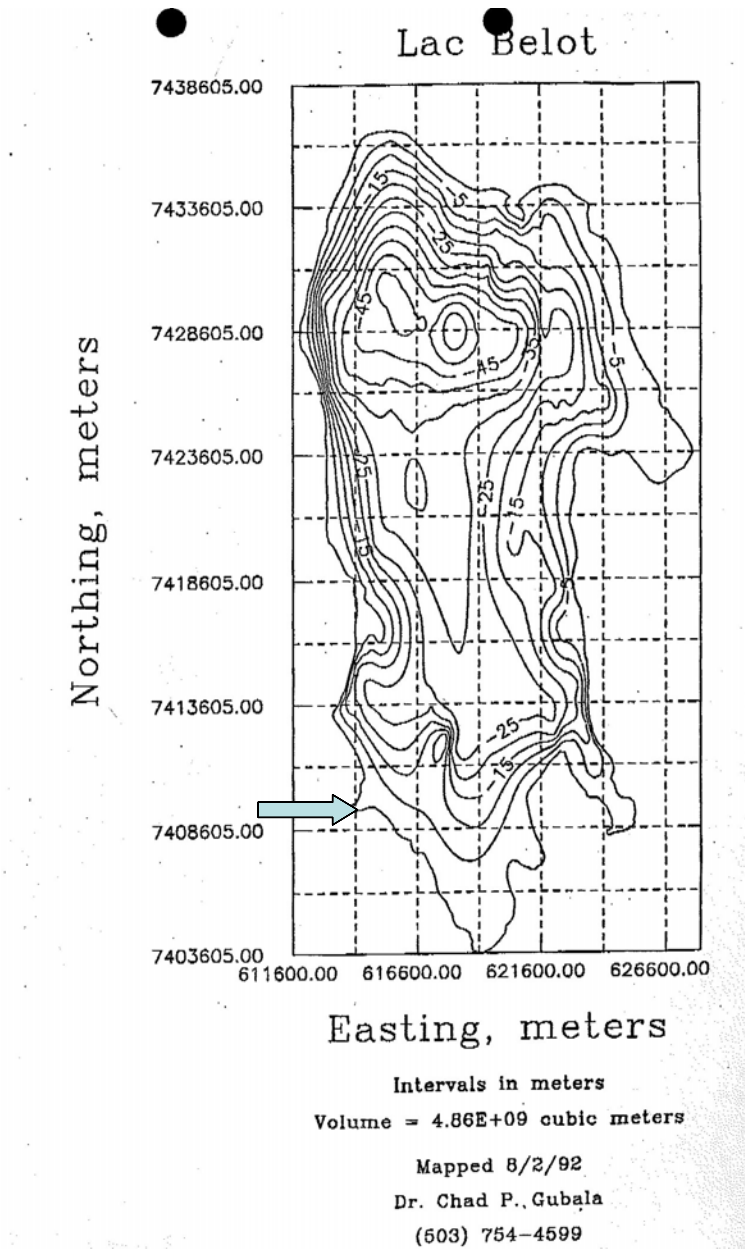
- Identify for special consideration in the land use planning process.



The legend of Neyadalin, the underground river. From the Report of the Sahtu Heritage Places and Sites Joint Working Group, pages 56 -7.

<u>Above</u> – another view of Lac Belot, seen from above the Ridge.

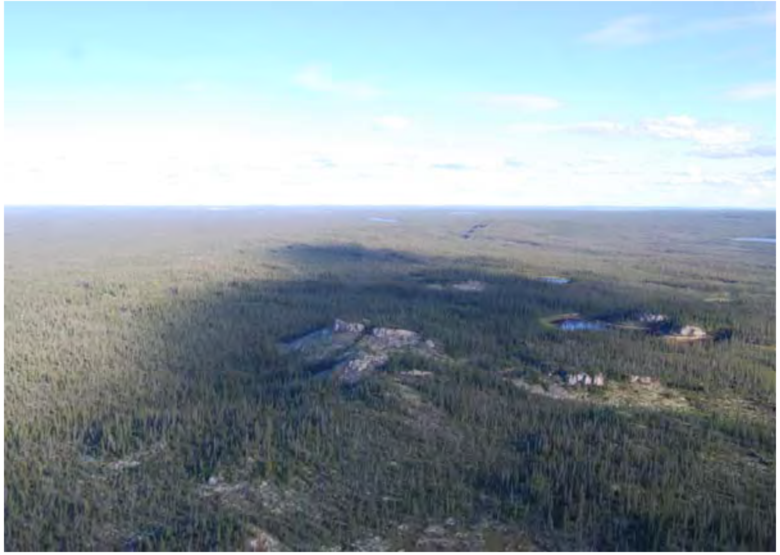
<u>Right</u> – the bathymetry of the lake. It has an area of 300+ km square kms and is estimated to store nearly five billion cubic metres of water. The arrow indicates where, according to the Neyadalin map on page 115, the outflow passes underground via a sinkhole. The water will pass beneath the Ridge or perhaps flow along it underground for some distance.

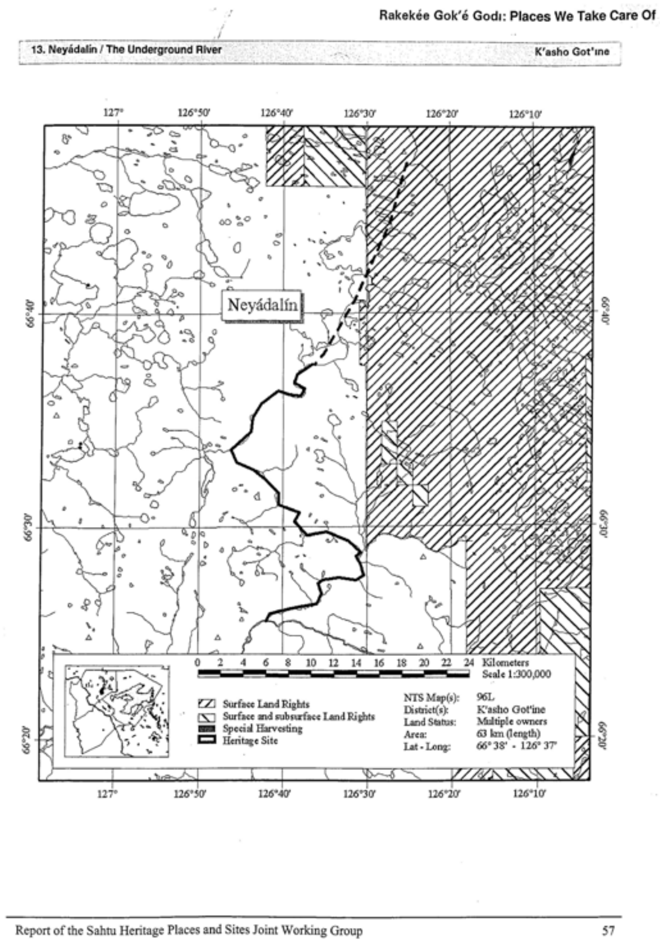


Aerial views of the crest (left) and western slopes of Lac Belot Ridge, looking south. This dramatic feature may have been created by the swelling consequent upon hydration of anhydrite lower in the Bear Rock Fm. Hydration converts anhydrite ($CaSO_4$) to gypsum ($CaSO_4 \cdot 2H_2O$), with a volume expansion up to 35%. The views certainly suggest upward violent folding and rupture. Hydration probably occurred along a glacier front, but before the last glaciation because there are glacial scours cut through the Ridge from place to place.

<u>Above</u> – there are some substantial sinkholes with ponds nestled against the Ridge and many shallower depressions along the crest.

<u>Right</u> – to the south Tunago Ridge is a similar feature. Tunago Lake is seen in the background.





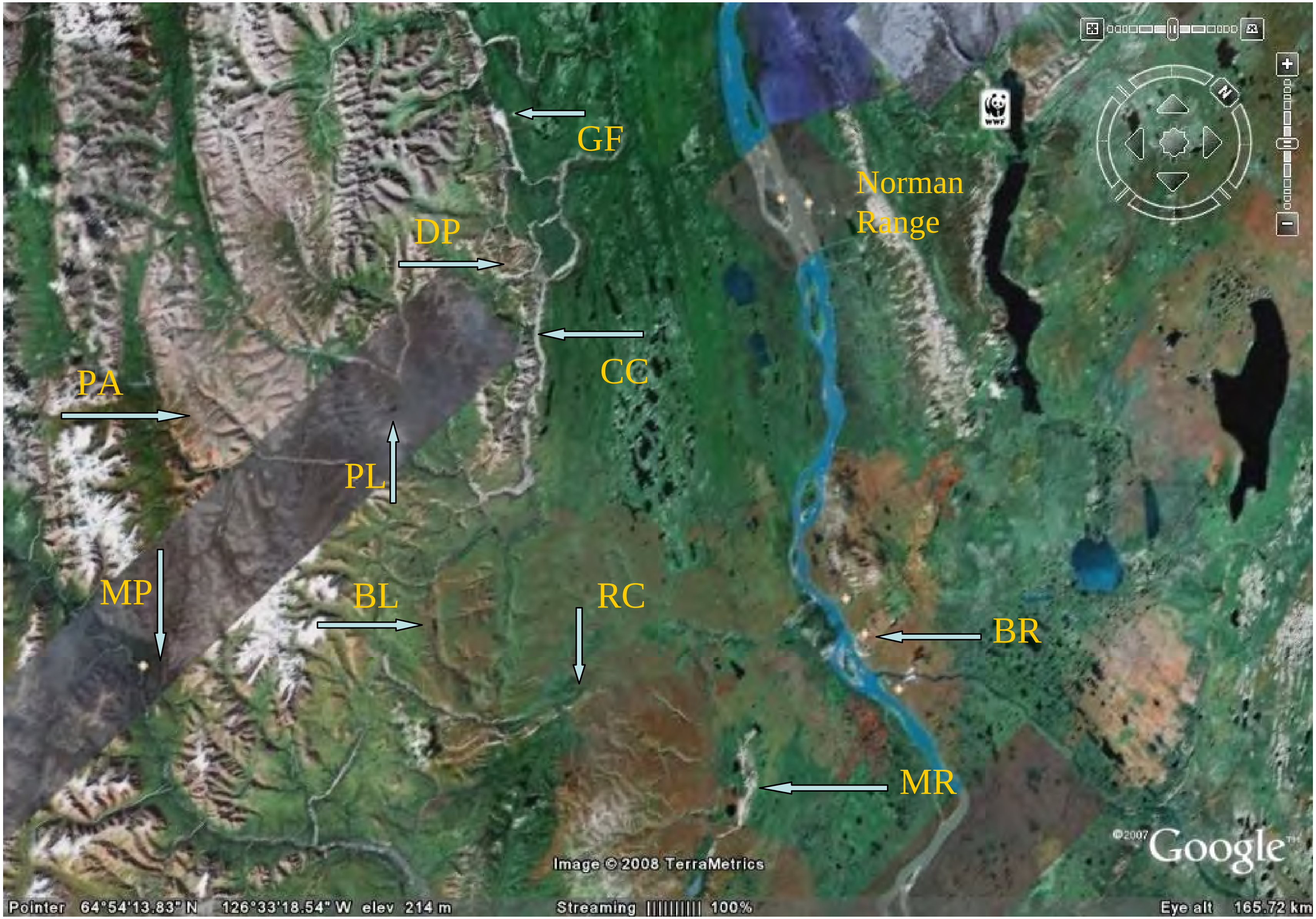
<u>Above</u> – **Lac Belot Ridge becomes weaker and discontinuous south of Lac Belot. The lake is at 255 m above sea level. To the North is Colville Lake at 244 m asl, separated from it by an isthmus on Mt Kindle dolomites that is only 3.5-6.0 km wide. Yet Lac Belot apparently drains southwest underground in the Bear Rock breccia. The straightline (= minimum) travel distance from the sink to the location of the springs suggested by the Neyadalin map (<u>above right)</u> is 20 km and the fall of height is 75 m, giving a hydraulic gradient of about 4 m/km. This is quite steep for karst in breccia, so the route in the legend of Neyadalin is certainly feasible.**

<u>Recommendation</u> – <u>that the karst between Lac Belot and the putative springs be investigated by air photo analysis, ground stops and at least one dye trace, with the expectation that a karst reserve will be proposed that complements the cultural reserve</u>.

Part 4 - The karst terrains west of the Mackenzie River

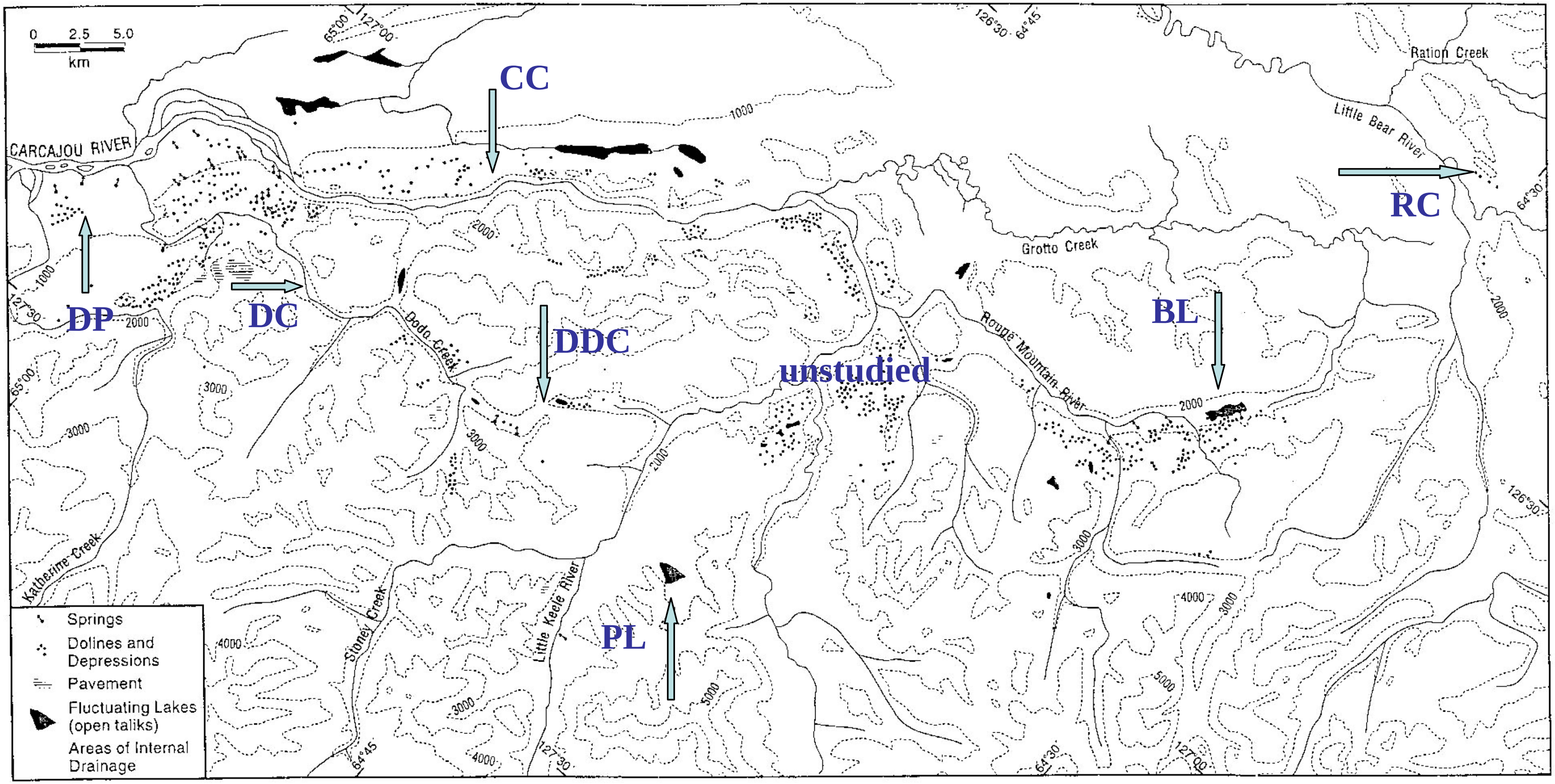
(A) The Mackay Range, Ration Creek and 'Bonus Lake'.

Sunset in the Mackay Range



PA = Plains of Abraham; MP = Moraine Polje; BL = Bonus Lake; PL = Pyramid Lake; DP = Dodo Pavements; GF = Great Fan; CC = Carcajou Canyon; RC = Ration Creek Sinkhole; MR = Mackay Range; BR = Bear Rock

Dr Jim Hamilton's map of karst depressions, karst lakes and springs between Little Bear River and the mouth of Dodo Canyon.



It is seen that there is a nearly-continuous strip of karst development along the front of the Canyon Ranges from Bonus Lake to the Dodo Pavements and further west. It is chiefly in Bear Rock breccia. Because of costs of access, one patch in the middle has been left unstudied to date. The Bonus Lake site is therefore treated as a separate outlier here but it is apparent that it could be included in the proposed Canol Geopark.

DP = Dodo Pavements; DC = Dodo Canyon. DDC = Dodo Dry Canyon; CC = Carcajou Canyon; PL = Pyramid Lake; BL = Bonus Lake; RC = Ration Creek sinkholes.

Mackay Range

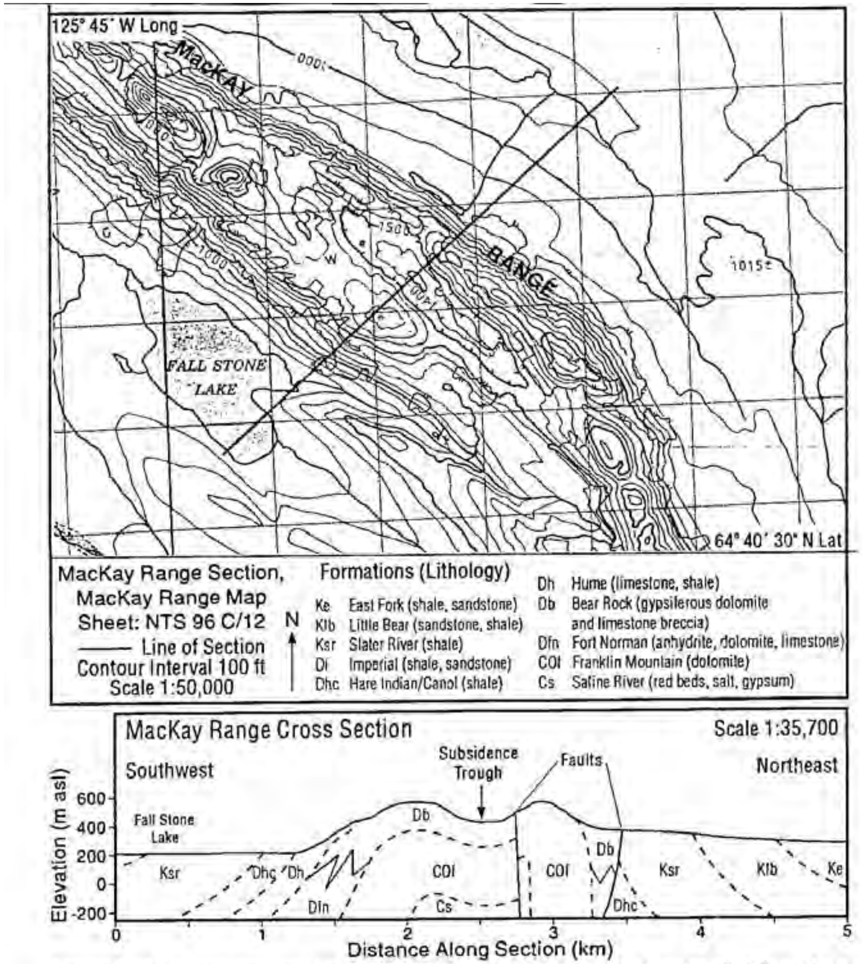
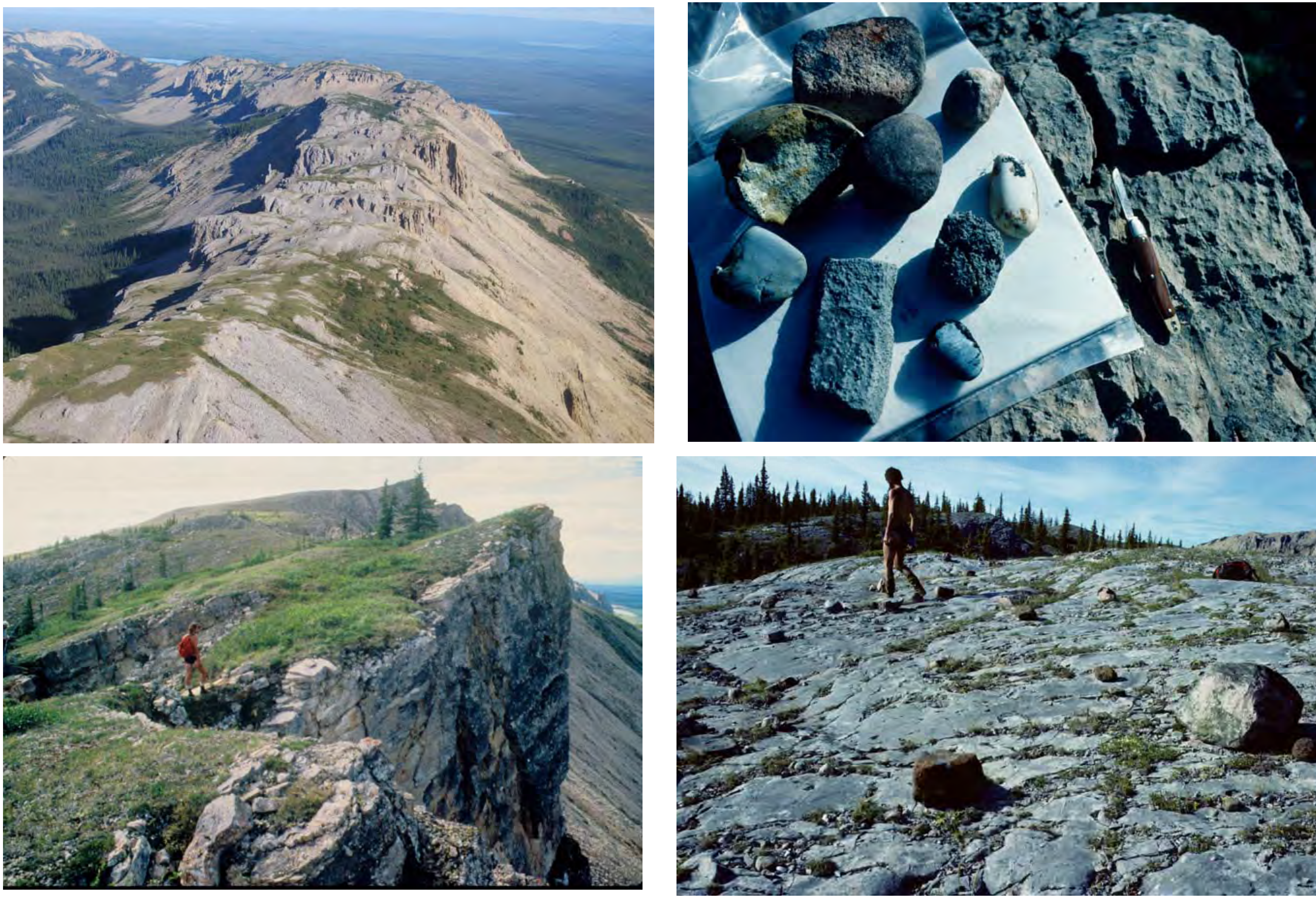


Figure 6.18: An anticline runs the length of MacKay Range. The northeastern limb is cut by a series of steep reverse faults, strata on both limbs dip sharply, locally approaching vertical. The Mount Kindle Formation is absent over this area. Along the crest of MacKay Range there are two large linear depressions interpreted as subsidence troughs. The northern trough is shown on the map above with a section below. Local well records (G-78: Table 4.3) indicate the Fort Norman Formation exceeds 300 m in thickness and the salt of the Saline River Formation is 150 m (Figure 4.8). The troughs are developed through subrosion of these units along the anticline crest and faults. Elsewhere on the range, dolines and karren occur on the Bear Rock and Hume Formations (geology after Cook and Aitken, 1976; Pugh, 1993).

The Mackay Range stands out as an isolated mountain range in the plains of softer, younger rocks on the western bank of the Mackenzie River. As Jim Hamilton's figure on left shows, it is an anticlinal fold of Mt Kindle dolomite and Bear Rock breccia with Hume limestones on the west flank and an important fault through the middle. There is a large central closed depression west of the fault. The Range rises abruptly to heights of 300-400 m above the plains, as shown in the northward view above.

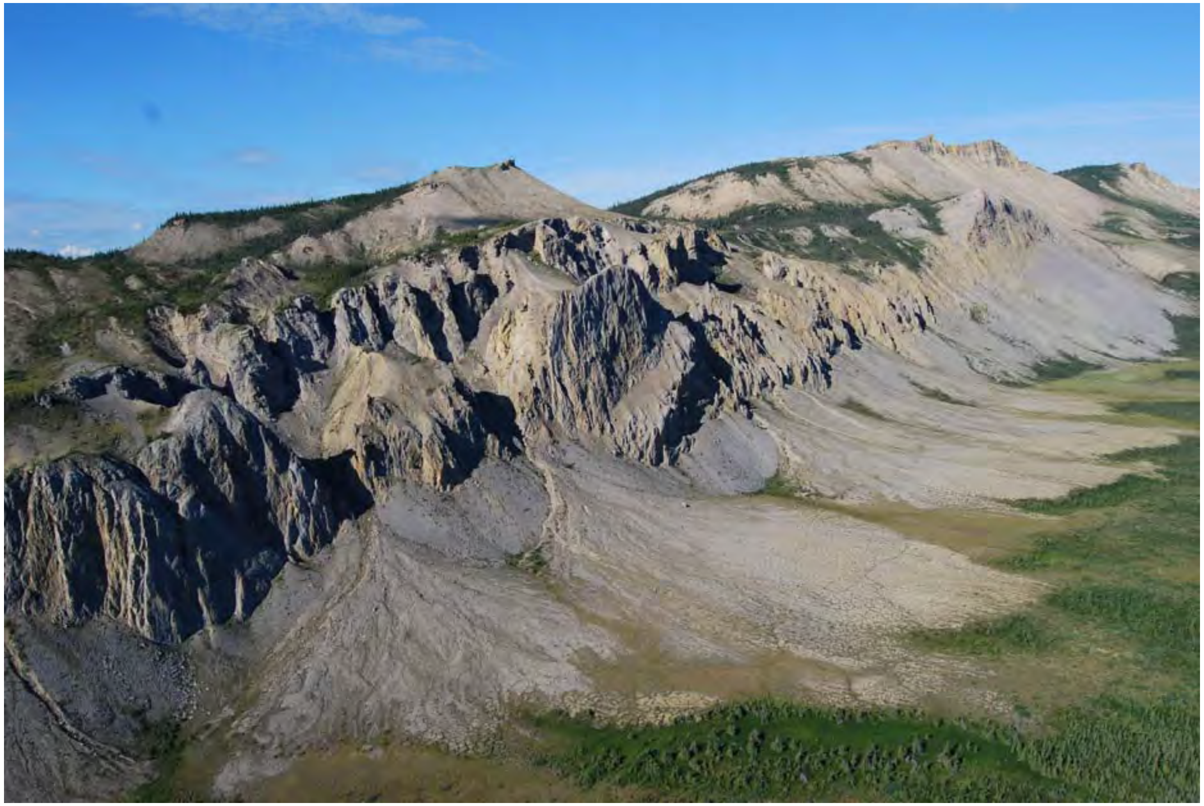
Looking down into the central closed depression from a point on the southeastern ridge. The depression was created by dissolution of Bear Rock breccia, and possibly by underlying solution of salt in the Saline River Fm as suggested by Hamilton. It and all other interior areas of the Range are drained karstically to small springs around the perimeter of the Range.

Looking southwest from a point on the crest of the Range. The trough created along the fault line is also clearly seen in this view. The vertical scarp face on the right is the edge of the Hume limestone, overlying the Breccia.

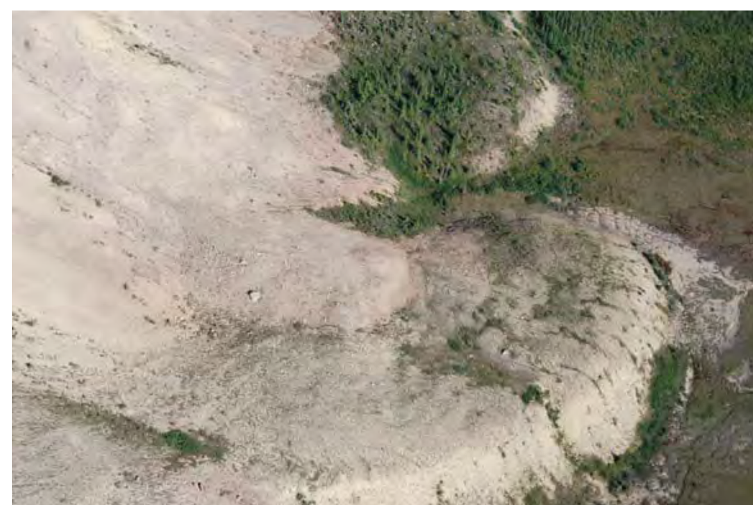


All of the Mackay Range was overridden by the Laurentide Continental Icesheet from the east. <u>Above right</u> – erratics collected along the crest. <u>Lower left</u> – a meltwater shaft lies behind the figure. <u>Lower right</u> – glacier scour and erratics on the limestone.

There are higher karst ponds above the central depression. Everywhere there is abundant evidence of vigorous frost shatter and solifuctual activity on the Bear Rock Breccia.



<u>Above</u> – very steeply dipping Bear Rock strata along part of the east face produce these beautiful talus fans with torrential debris flow channels in some of them.
<u>Below</u> – accumulation of ground ice in the base of this fan has converted it into a rock glacier.



Springs emerge from the talus fans at several points along the east and west faces of the Range, creating local oases. A stop was made at the example shown here at N 64 42.95, W 125 42.87, at an elevation of 333 m above sea level.
Note the debris flow channels seen behind the figures and the unusually bright lichen colonisation of a dolomite block shown on right.

The Mackay Range exhibits many attractive features such as the talus, patterned ground and springs seen here. However, its landforms are similar to those of Bear Rock itself but not as varied or well developed in many respects, so it is not recommended for special protection.

Ration Creek Sinkhole

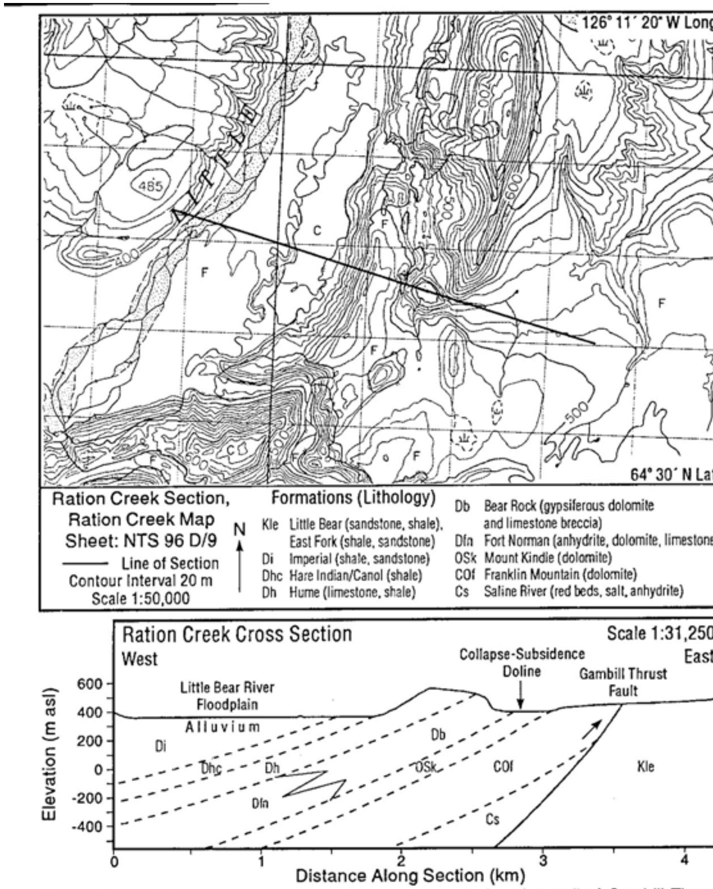


Figure 6.14: Dolines and linear depressions occur on the hanging wall of Gambill Thrust, east of Little Bear River. The largest feature, Ration Creek Doline, is an oval shaped, steep walled sink located within a linear trough. The trough is in the Bear Rock Formation, its axis is parallel to strike. The doline extends into the Mount Kindle Formation. The morphology suggests a collapse-subsidence origin. Subrosion originates in the Saline River Formation which subcrops 500 to 600 m below the feature (after Aitken and Cook, 1974; Pugh, 1993).

West of the Mackay Range a shallow ridge of steeply dipping Bear Rock and Hume strata rises above the general level of the Mackenzie Valley. It is well rounded by glacial action. A large sinkhole abruptly interrupts it a short distance south of Ration Creek.

Aerial view of the sinkhole from the east. The location is N 64 31.20', W 126 15.30'. The water is at 380 - 400 m asl. It is seen that this is a collapse in steeply dipping rocks, Mt Kindle dolomites in the foreground and Bear Rock breccia behind. This sinkhole therefore offers a sharp contrast to the Vermillion Creek collapse sink (page 54) in horizontally bedded rocks.

Three further perspectives flying around the sinkhole. We have not visited it on the ground. A small stream flows in at the east end and two possible sink points are seen towards the west end.

The ground water probably drains to the Little Bear River valley, which is two km to the west at 360 m asl. In the past geologists have suggested that the collapse was caused by dissolution of the Saline River salt far below but it is considered as likely to be due to the local stream dissolving the Breccia.

Ration Creek Sinkhole is one of the finest examples known in Canada and offers an excellent morphological contrast to Vermillion Creek Sinkhole.
<u>Recommendation - that Ration Creek be considered for protection with Vermillion Creek as a truly spectacular pair of karst depressions.</u>

The Glacial Scablands Karst of “Bonus Lake”.

This was the author’s first view of the lake, 10 August 1983. It has no formal geographic name. In an air photo review of the region he had missed the rugged karst topography on the left (west) bank and so called the unexpected find “a bonus”. The lake drains underground near a prominent grotto, so “Grotto Lake” may be more appropriate.

Aerial view from approximately the same position as page 135, but taken on 2 August 2007. The view is downstream along a major glacial spillway. The lake is impounded by the detrital fan behind it. It appeared to be draining into a karst sink at the arrow. The water flows underground in the grey limestones on left and resurges at springs by the smaller lake seen in the far background.

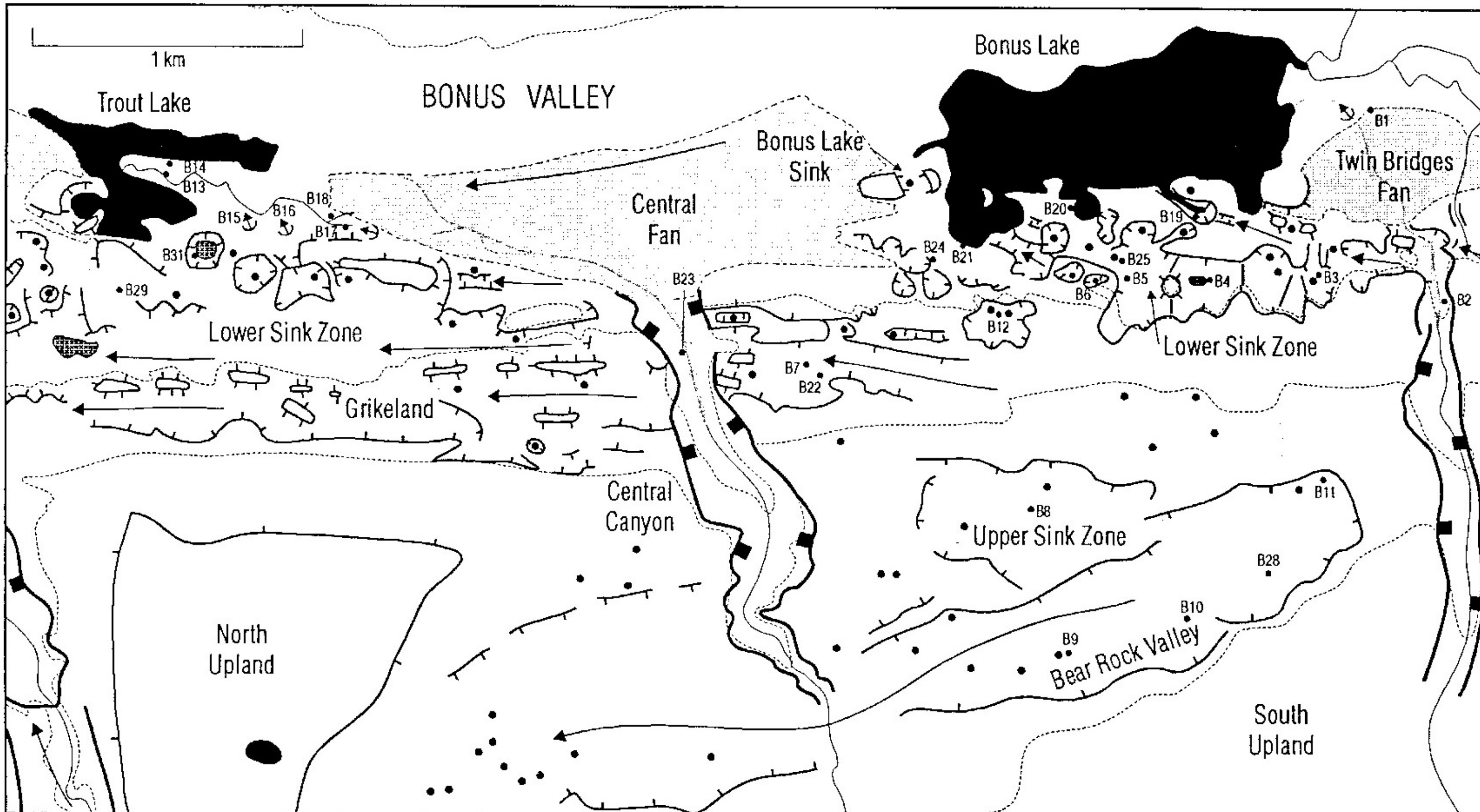


Figure 8.4: Karst geomorphology of the core area of the Bonus Lake Site. The Upper Sink Zone is a recharge area of shallow dolines and depressions. The Grikeland is an area of corridors and tower forms. The Lower Sink Zone has corridors, compound depressions and breached sinks. Infilled and drowned dolines extend onto the floor of Bonus Valley. Springs discharge from the alluvium of the fans and at the base of the Lower Sink Zone.

- Canyons
- Steep Slopes
- Contour Interval: 100 m
- Streams
- Ephemeral Streams
- Fans
- Alluvium
- Ponors of diameter > 5 m
- Dolines: defined by steep slopes
- Sinking or perched ponds in dolines
- Breached Dolines
- Springs
- Tower
- B8 Water Sampling Points
- Meltwater Channels

This geomorphic map is from Jim Hamilton's PhD studies with the author, categorising the karst landforms and showing that the groundwater flows to springs at 'Trout Lake' (informal name) at the head of Grotto Creek.

<u>Left</u> – approaching the Bonus Lake Spillway from the east. The spillway is seen to be sharply entrenched into a broad plateau, with the Canyon Ranges of the Mackenzie Mountains rising gently behind it.

<u>Right</u> – looking southwards up the Spillway. Its floor is entrenched in the weaker shaly rocks of the Hare Indian, Canol and Imperial formations. The resistant limestones of the Hume Fm, (dipping gently to the left in the photo) form the western wall. Spillway flood action has enlarged prior karst landforms and scoured new river forms in them and into Bear Rock breccia underneath.

In four previous study visits neither Dr Hamilton or I had seen Bonus Lake as low as it was when our party flew in on 2 August 2007. Presumably the lake (marked as a permanent feature on the topographic maps) drains dry in winter. The sub-circular depressions at the foot of the limestone are mega-flood scours, beautifully streamlined at bottom right.

The three mega-flood scours in the limestones of the west bank, from upstream (<u>top left</u>) to downstream (<u>lower right</u>).
Note also the meandering stream channel beneath the water. The nature of the several linear features crossing it is not known – possibly tracks from ATVs?

The scour holes appear to be functioning as ebbing-and-flowing wells (Fr – *estavelles*), discharging water under wet conditions and swallowing it in droughts. The upstream scour (above) was still discharging weakly on 2 August 2007 (arrows) but the downstream scours will have been swallowing its output.

<u>Above</u> – the central and downstream scour features.

On 2 August 2007 the air was full of insects and rich with the scent of wild mint.

The Hume limestone is dissected into a series of corridors by karst and mega-flood action. They are undermined by dissolution in the more susceptible Bear Rock breccia beneath the limestone. The Grotto (right) has an impressive portal but shrinks rapidly, pinching out in a fill of permafrozen silt about fifteen metres inside.

<ins>Above </ins>– looking out of the Grotto.

<ins>Right</ins> – the Bonus Lake Karst includes a fine example of a natural bridge. It is formed in the Bear Rock breccia.

<u>**Above left**</u> **– looking north down the Spillway, with a storm approaching. 'Trout Lake' and the rugged terrain to its left are the northern end of the Bonus Lake Karst Area.**

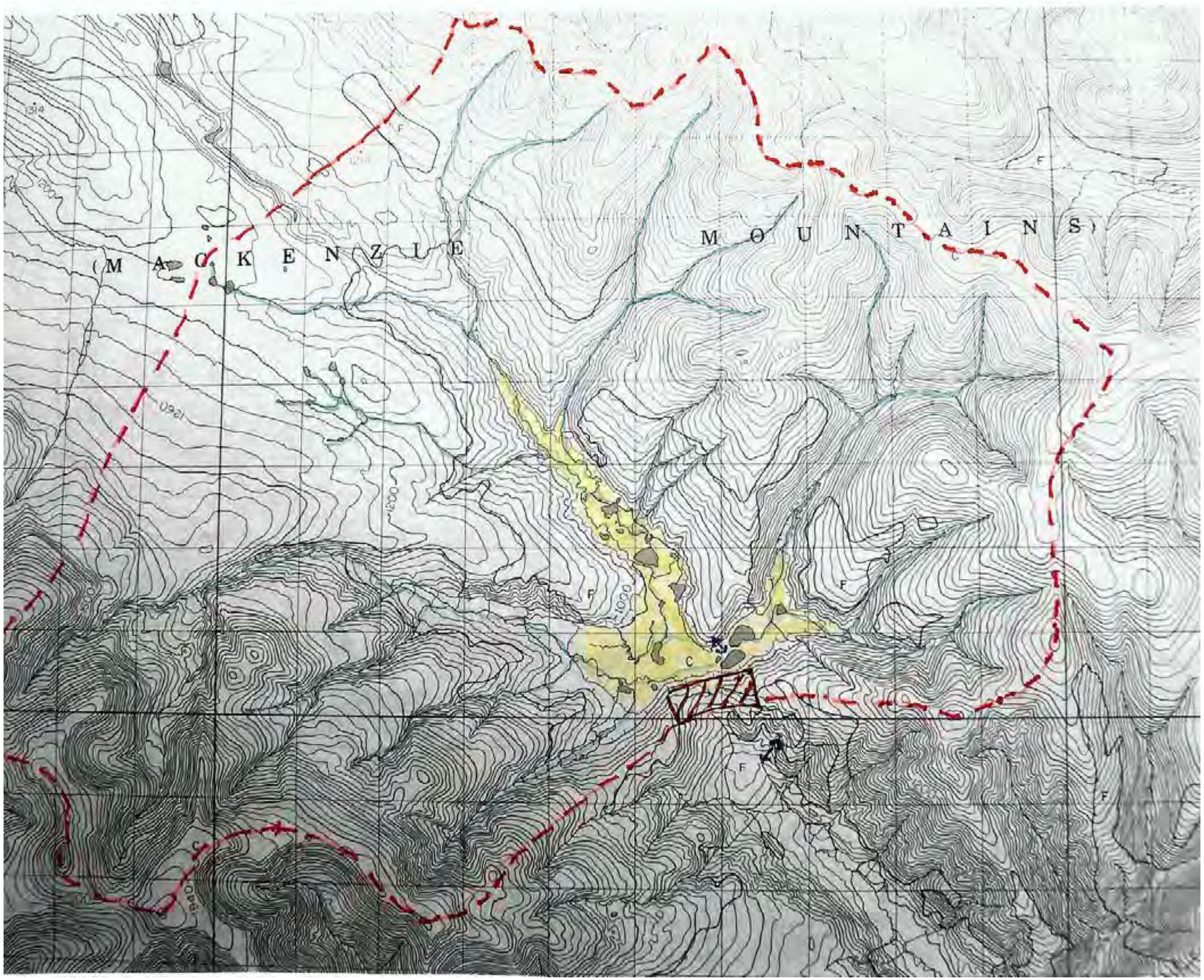
This scabland karst is a gem, a place of exceptional beauty. Already, I am informed, it is attracting family camping from Norman Wells. Dr Hamilton's geomorphic analysis is attached as Appendix B to this Report.

<u>**Recommendation – that the Bonus Lake (or Grotto Lake) Karst receive the fullest available recognition and protection, either as a site on its own or as a component of an international geopark centred upon the Canol Heritage Trail.**</u>

(B) Moraine Polje

An astonishing feature! – in its furthest incursion into the Keele River valley the Laurentide Glacier front reached the position between the arrows in the rear of the picture and built a terminal moraine there. This blocked surface stream flow out of the valley in the foreground, which has never been glaciated. The valley became partly filled with alluvial debris and the water developed an underground karst exit through the bedrocks, the Mt Kindle dolomites.

Blockage of drainage by terminal moraines is a common phenomenon in glaciated regions. In almost every case, however, the valley upstream will fill to overflowing and then entrench a channel through the moraine ridge, draining any temporary lake. At Moraine Polje, the moraine ridge (arrow) shows no evidence of entrenchment, indicating that the impounded lake quickly opened its karst route.



Topographic map of the Moraine Polje basin. The grid has one km squares. Contour interval is 20 m. Red = topographic watershed. Yellow = the alluvial floor (infilling). Brown quadrangle = approximate extent of the moraine dam. Northern blue arrow = stream sink. Southern blue arrow = the spring. The area of the basin is ~90 square km.

The entire basin is in the Mt Kindle dolomite formation, weathering grey to rusty red. There are a few tors along the ridge crests and a very extensive periglacial erosional pediment which bevels the steeply dipping strata.

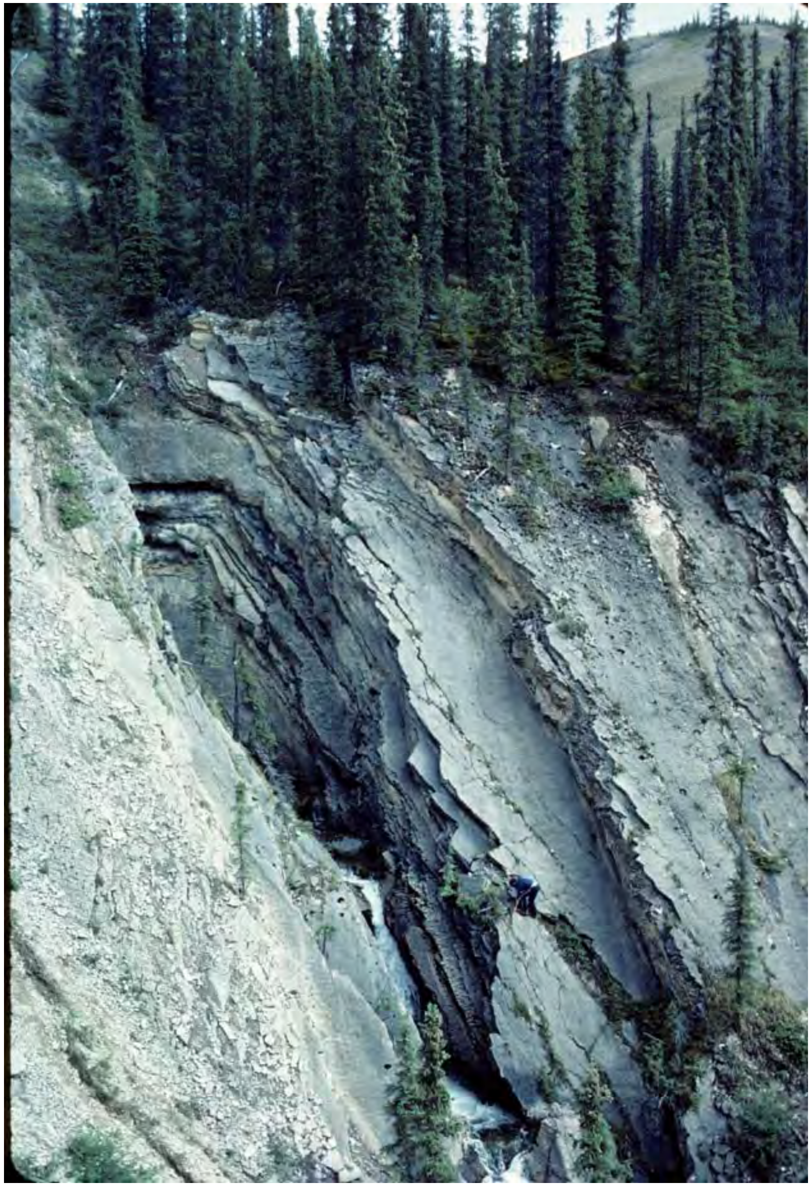
<u>Left</u> – the stream sink of Moraine Polje viewed from the crest of the moraine in 1983. <u>Below</u> – viewed in 2007. The sink point and the shallow ponds on the alluvium have been very stable over this time period.

The polje has developed in a steep, V-form syncline (downfold). Curiously, the stream has sunk into the rock north of the alluvial flat in the pictures instead of into the same strata on the south side (shown by horizontal arrow), which are much closer to the spring outlet.

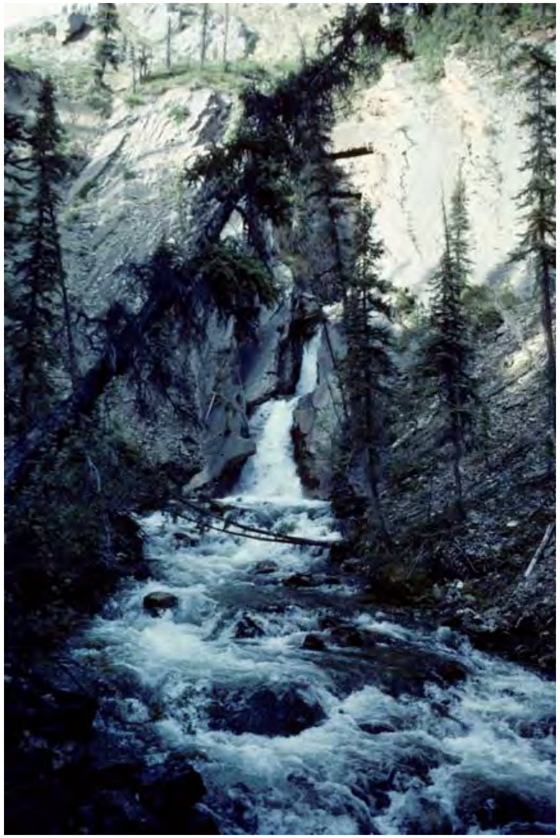
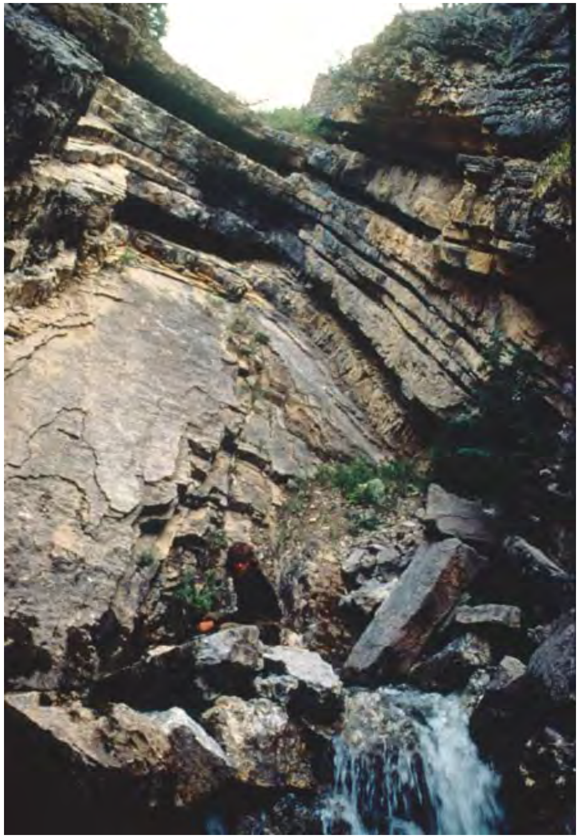
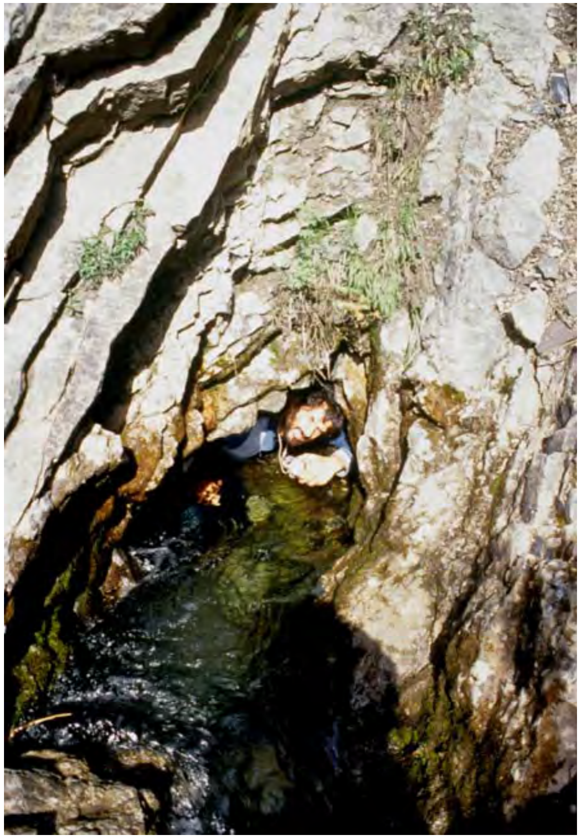
On the ground – the high water mark in the polje is clearly seen near the stream sink. Floods are undercutting the dolomite cliffs nearby, creating the corrosion notch seen top right.
<u>On right</u> – looking down onto the polje stream flowing into the cliffs on the north side of the polje.

The stream sinks into a cave of enterable dimensions. <u>Top left</u> – the author injecting fluorescein tracer dye on the first visit, August 1983. The water had warmed in the shallow approach channels and was a pleasant 14 C. <u>Top right</u> – the entrance in August 2007. There has been one fall of roof rock in the centre of the entrance arch; otherwise the scene is unchanged from 1983.

From the entrance the cave opens up into a substantial chamber formed by rockfall ('breakdown chamber') and plunges down a small waterfall. Beyond it is the wet and constricted passage shown above. This may be explorable in winter when there is no water flow but I do not believe that it will be enjoyable! The cave is a very raw, young feature formed as a consequence of the Moraine blockage. There are no sediments or speleothems of interest, and no faunal remains were seen.



The spring is a truly astonishing feature, appearing as if a giant fist had punched out from inside the rock to release the pent-up water.

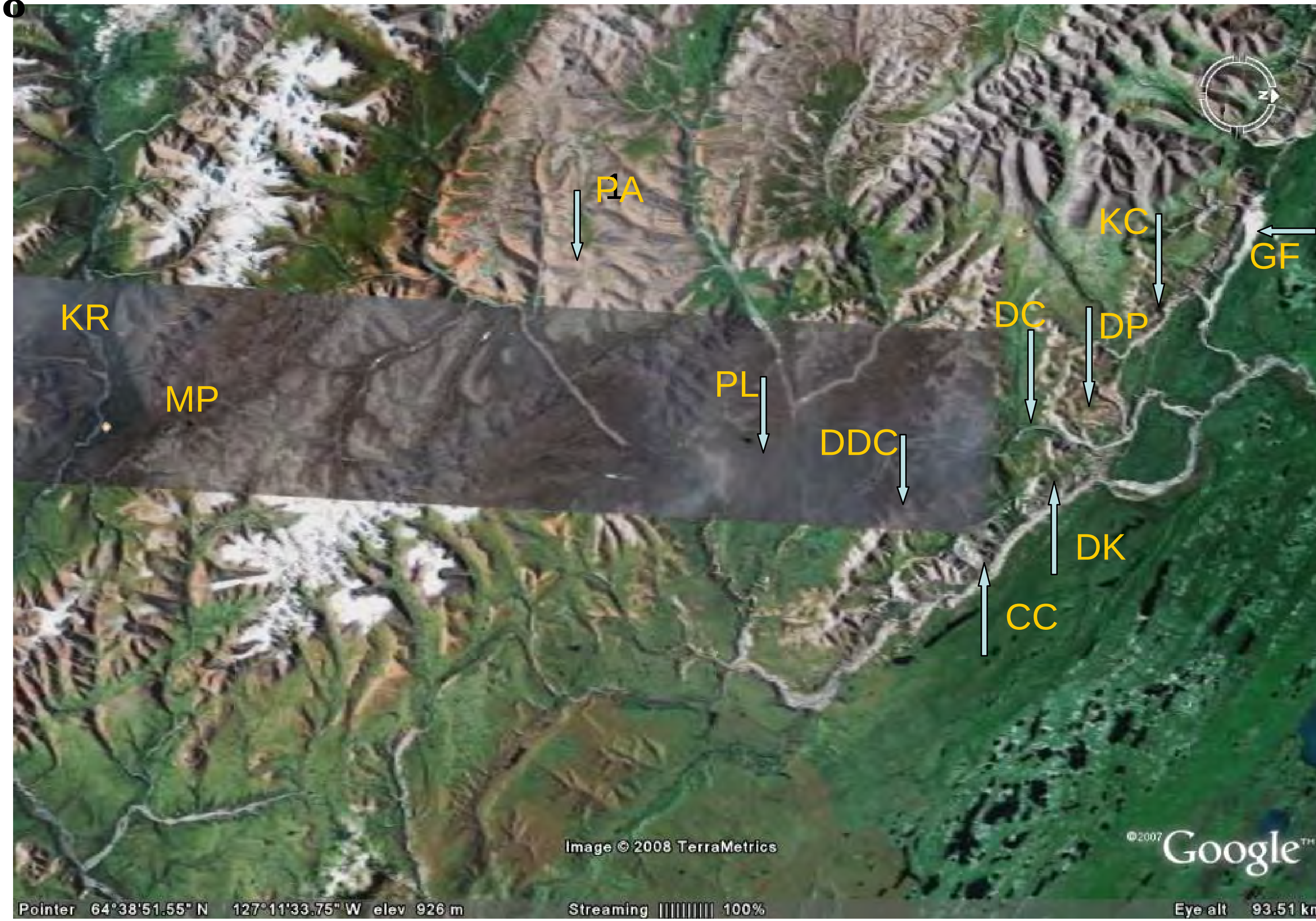
<u>In the spring orifice.</u> The spring quickly 'sumps' (becomes waterfilled). It is impassable under summer flow conditions and possibly too constricted for human entry at any time. It is ~1300 m distant from the cave in a straight line. Our fluorescein dye appeared at visible strength (green colour) in it five hours after injection at the stream sink. This result gives a minimum ground water flow rate of 300 m/hour. The actual rate will be somewhat faster because the flow will not follow a simple straight line. It indicates that the cave must be a pipe large enough throughout its course to permit turbulent flow.

Moraine Polje is the best example I have seen of glacial moraine blockage creating a large karst feature. It is an outstanding example of karstic drainage exploiting an obstruction to surface river flow to capture the water underground, all the more remarkable because it happened very rapidly in dolomite, the least soluble type of karst rock.

<u>**Recommendation – that Moraine Polje be protected as a glaciokarst landform of outstanding quality and geomorphological significance.**</u>

C) Karst, Periglacial and Glacial Landforms of the Canyon Ranges from the Plains of Abraham to Carcajou, Dodo and Katherine canyons: the components of a proposed UNESCO International Geopark that broadly follows the Canol Heritage Highway.

A traverse from the Plains of Abraham in the interior of the Canyon Ranges to the mouths of the canyons debouching onto the Mackenzie Valley lowlands passes through a rich variety of sedimentary rocks and of geological structures. It begins in an area never glaciated but subject to intensive periglacial conditions during the glacial periods and still retaining deep permafrost today, passes through a narrow zone of older glaciations into a mountain front sector overrun and scoured during the final glacial advances and then eroded with catastrophic rapidity by some giant melt rivers along the NW edge of the Laurentide Continental Icesheet.
All of the karstic rocks mentioned in this report (limestone, dolomite, breccia and salt) can be seen undergoing modern dissolution along the traverse, and there are many other geomorphic processes vigorously at work on both the soluble and the insoluble strata. It is a region of outstanding geologic and geomorphic interest that also offers landscapes of considerable aesthetic appeal.



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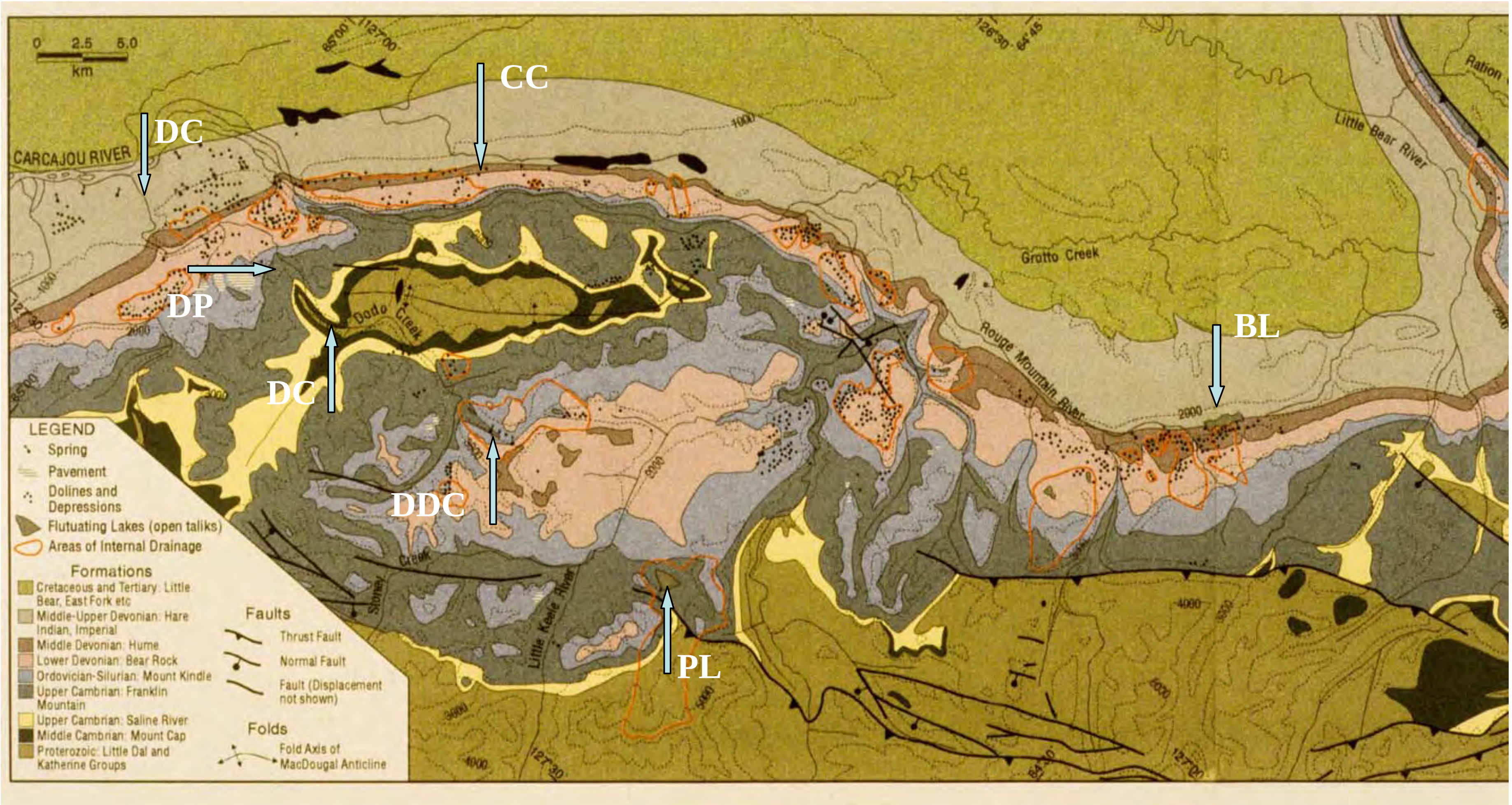
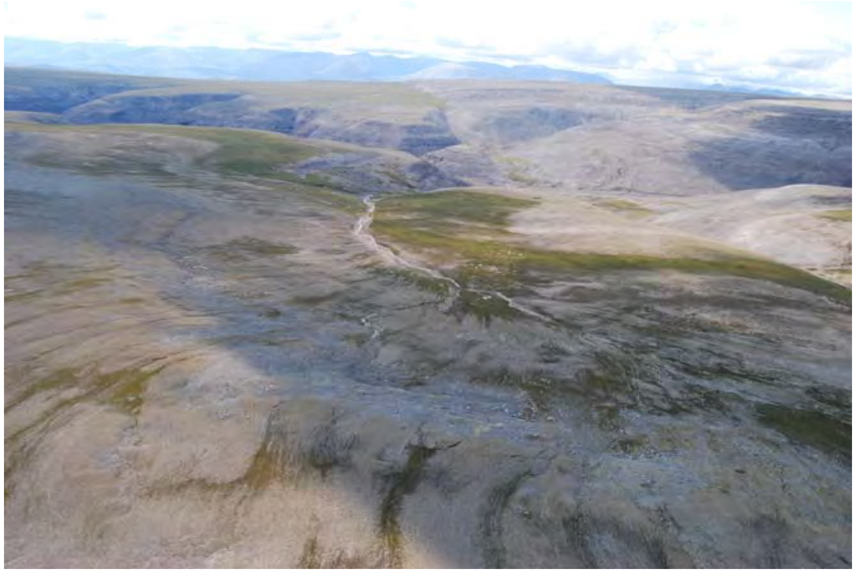
A Google Earth overview of the proposed International Geopark. KR = Keele River. MP = Moraine Polje. PA = Plains of Abraham. PL = Pyramid Lake. DDC = Dodo Dry Canyon. DC = Dodo Canyon. DP = Dodo Pavements. DK = Drape Karst. CC = Carcajou Canyon. KC = Katherine Canyon. GF = Great Northern Fan.



This section of the 'Carcajou Canyon' geological map illustrates the variety of bedrocks and structures traversed between Pyramid Lake (PL) in the south and Carcajou (CC) and Dodo (DC) canyons in the north of the Canol Road traverse. DDC = Dodo Dry Canyon; DP = Dodo West Pavements; BL = Bonus Lake.

The Plains of Abraham

The Plains of Abraham are an extensive plateau in the central unglaciated zone, formed of horizontally bedded dolomites of the Mt Kindle and Franklin formations. Elevations are generally between 1500 -1700 m asl, placing the Plains in the arctic tundra biozone. In this view we are approaching them from the south, with Carcajou River at their foot 500 m below them.

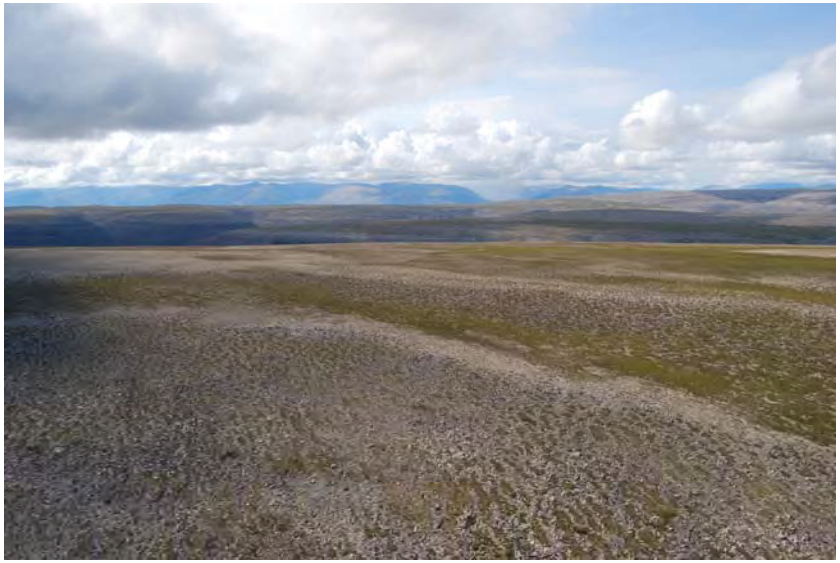


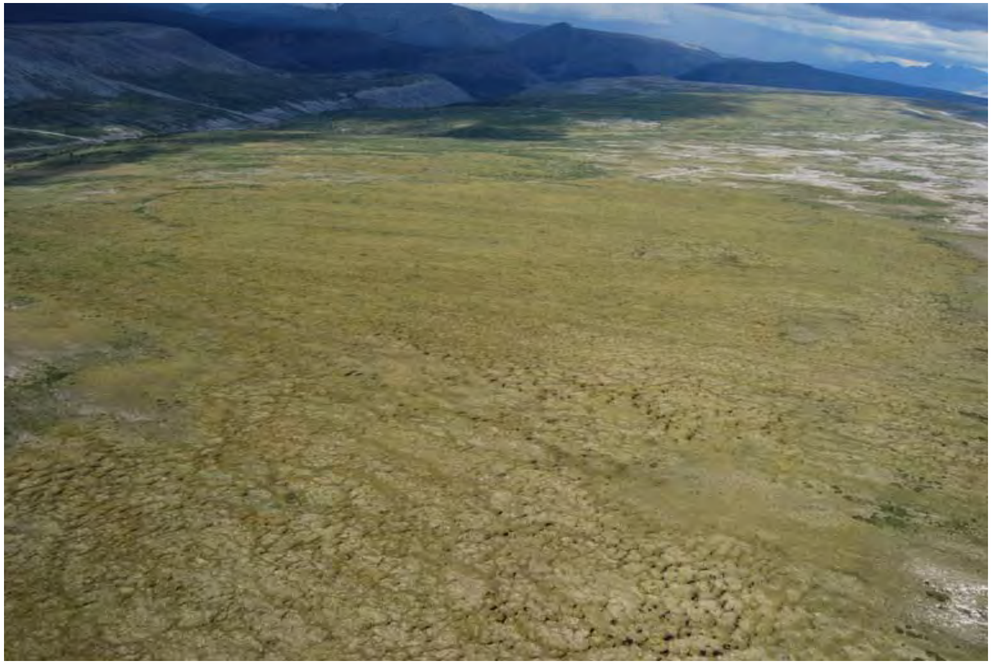
The high Plains display a wide but subtle variety of forms, determined by slight differences in the susceptibility of dolomite beds to frost shatter or dissolution, or microclimate or hydraulic gradient factors.

Above left – an 'altiplanation terrace' (grassy) caused by recession of the little scarp above due to frost attack combined with groundwater. Above right – slightly less soluble beds support a shallow stream channel at the surface. Right – remains of a Canol camp.

Varieties of patterned ground above an elevation of 1600 m where growth of grasses is very limited.

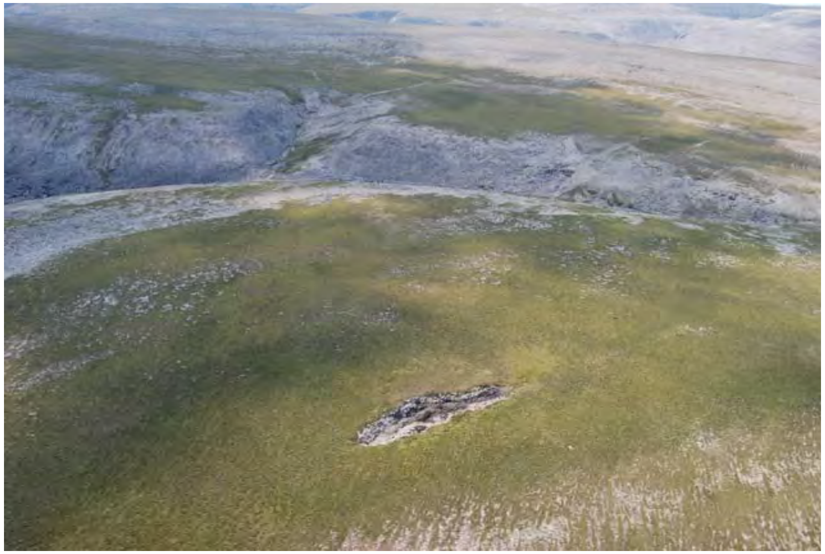
A superb display of stone stripes





Patterned ground and lobate flows at lower elevation where grasses and other alpine plants are more abundant.

Frost polygons in a massively bedded dolomite that displays some good solutional pittting.



Despite the severe climate and deep permafrost there is some karstic drainage even on the highest ground.

<u>Above</u> – two small sink points on plateau tops.

Right – a 'steephead' (or 'pocket valley') created by springhead sapping on the flank of the plateau.

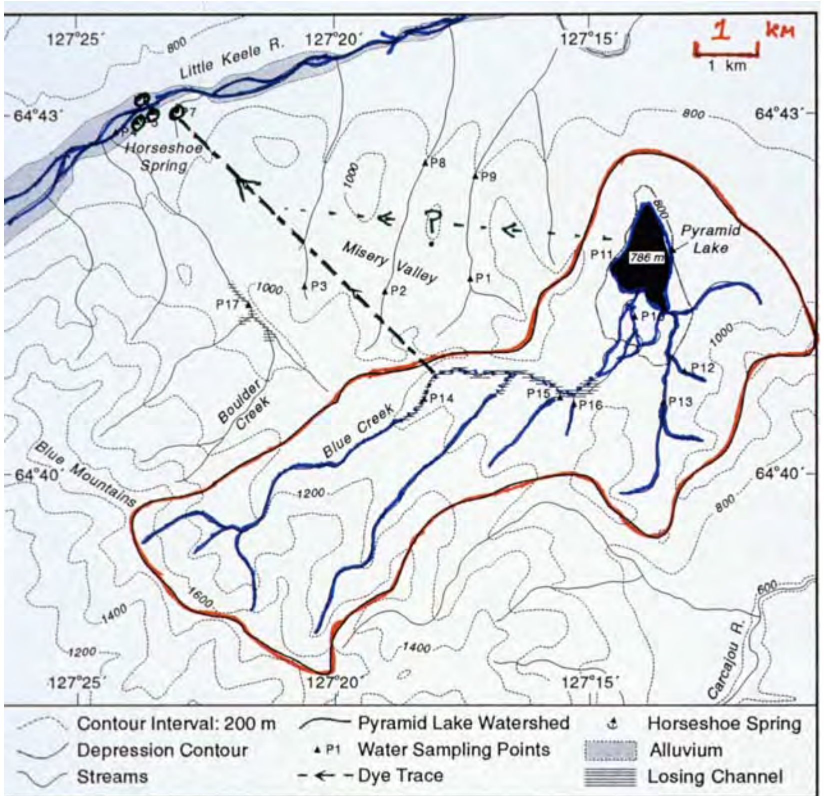
This is the finest steephead I have seen in any alpine or periglacial region. Water seeps out along the foot of the arcuate cliff in massive, resistant dolomite, sapping it back by a combination of solution and frost shattering. The water surfaces from springs at the base of the talus below, creating an oasis.
The Canol Road passes by the crest.

The oasis is at N 64 33.7’, W 127 18.6’. Its floor is at an elevation of 1450 m.

<u>On right</u> – a line of tiny caves can be seen in the prominent bedding plane at the base of the massive dolomite bed. These caves are now abandoned as the groundwater has moved down to another exit plane masked by the top of the talus.

The Pyramid Lake Polje

Pyramid Lake is located at N 64 42’, W 127 15’. The lake surface is at 786+/- m above sea level, fluctuating a little seasonally. It occupies an alluvial lowland, is drained underground karstically, and thus functions as a karst polje. This view looks south across it towards the Plains of Abraham. The Canol Road is at the foot of the hills behind the lake.



Above – Jim Hamilton's map of Pyramid Lake Polje. It has a catchment basin area of 34.4 sq kms. Water sinks in the Blue Creek channel bed upstream of the lake, where it was dye traced to 'Horseshoe Springs' (unofficial name) with a flow time of four days or ~1500+ m/day. The underground flow broadly follows a synclinal downfold in Franklin Mountain dolomites, i.e. this is a polje determined chiefly by geological structure.

The bedrocks in the Pyramid Lake basin range from Proterozoic quartzites (Blue Mountains in rear of the picture), to the Bear Rock breccia. The groundwater flows through Franklin Mtn dolomites and follows a syncline. The area was glaciated during the ancient Katherine Glaciation but escaped later glacier action. It is dominantly a periglacial landscape of intense solifluction creating long, gentle footslopes (cryopediments). It displays many morphological similarities with Moraine Polje but has a different origin. This pair of large sub-polar poljes thus nicely balance each other in genetic terms.

Falls of the Little Keele River

From Pyramid Lake the Canol Road winds north across the Little Keele River (which is actually a tributary of Carcajou River). These attractive Falls on the Little Keele are over Mt Kindle dolomites, with Bear Rock breccia in the background. The region escaped themost recent glaciation and offers fine cryopediment landscapes.

Dodo Dry Canyon

The Dry Canyon is a magnificent feature. It was carved by the Little Keele River which was then diverted to Carcajou River by glacial action, robbing Dodo Creek of its principal headwater and leaving its upper canyon dry. It is developed in Franklin Mtn and Mt Kindle dolomites and minor Bear Rock. The waters that it captures today all sink underground.

<u>Above left</u> – the Canol Road uses the gentle southern end of the canyon but then diverts east to find an easier route to the north.

<u>Right</u> – the first sinkhole in the upper canyon.

<u>Above left</u> – sinkholes in the upper canyon. The rock is the top of the Mt Kindle dolomite with weaker Bear Rock eroded back from the rim. <u>On right</u> – the principal sinkhole in the upper canyon, seen on 30 July 2007. The location is N 64 57.7’, W 127 18.65’. Elevation is 602 m above sea level. The whereabouts of the springs is unknown.

Below the upper sinkholes there is a steep bedrock step down (a paleo-waterfall) to the intermittent lake site shown in these two pictures. <u>On left-</u> the lake as it was on August 7 1983; <u>on right</u> – it was much reduced when seen again on July 30 2007.

The middle section of Dodo Dry Canyon shown looking upstream (south) <u>on left</u> and downstream <u>above</u>.
An outstanding feature of the canyon is the manner in which great aprons and fans of dolomite talus sweep in from either side.

A further feature of the middle canyon is the apparent occurrence of paleokarst depressions and deposits in the cliffs. After deposition of the Franklin Mountain dolomite there was a long period of surficial erosion before deposition of the Mt Kindle dolomites began. Karst sinkholes formed and filled with terrestrial sediments, the buff, orange and yellow patches shown in these photographs.

The climax of Dodo Dry Canyon is the northern (downstream) end where it is more than 350 metres deep. The lake is at N 64 49’, W 127 14’, at 600 m asl. Dodo Creek at the head of its canyon is in the background.

Another striking geomorphic feature of the Dry Canyon is the occurrence of 'debris flow' channels and fans. As the name suggests, a 'debris flow' consists of a mass of pebbles or larger rocks suddenly releasing and flowing downhill like a mass of water, carving a channel along their course, in this case in talus slopes. Debris flows occur in response to heavy rain or sudden melting of interstitial ice. They are quite rare, usually seen on weak volcanic rocks or sandstones. The debris flows in the Canol dolomites are the finest I have seen on any of the karst rocks.

Dodo Creek Canyon

Dodo Creek has entrenched its course across the flank of a major anticline (upfold) in the strata. As a consequence it first passes down through progressively older rocks to the crest of the anticline and then back up through them to its mouth. It is a very colourful journey, as this picture from the southern (upstream) end suggests.

Some features in the upstream end of Dodo Canyon. <u>Above</u> – a bedrock meander spur in sandstones of the upper part of the Saline River Fm.

Right – a recent landslide in redbeds (red shales) a little lower in the strata of the Saline River Fm.

Looking downstream at the final steep rise of the anticline to its crest. The rocks are shales and sandstones of the Mt Cap Formation.

The start of the lower canyon where strata dip in the downstream direction and the cliffs become higher.Here the top of the redbeds is beautifully exposed. Note that one block has settled below the others, probably due to salt dissolution below. Inset – the ruins of a Canol camp glimpsed in the main picture.

A further scene in the redbeds sector of Dodo Canyon. Another differentially settled block is seen where a tributary stream enters.

Left – a few hundred metres further downstream the redbeds have dipped below the Canyon floor and the walls are now in dolomites and shales of the uppermost section of the Saline River Formation

Right – proceeding downstream, in the left foreground the final shaly dolomites of the Saline River Fm dip below the canyon floor and very distinctive orange beds of the Franklin Mountain dolomites appear.

This is one of the finest scenes in Dodo Canyon. The orange Franklin Mountain dolomites dip into the canyon floor and the more massive, dark grey and steeper cliffs of the Mt Kindle Formation appear behind them. This is the deepest part of the canyon, the walls being more than 400 m in height.

In Dodo Canyon the Franklin Mountain dolomites display some attractive pinnacles and bright reddish orange patches of paleokarst sinkhole fillings.

<u>Upper left</u> – the Franklin Mtn dolomites pass below the Canyon floor. <u>Upper right</u> – the Mt Kindle dolomites have also dipped below the floor and a prominent 'gatepost' marks entry into Bear Rock breccia sector of the Canyon. <u>Lower right-</u> a surviving remnant of the Canol Road here.

<u>Upper left</u> – the Canyon becomes shallower as Bear Rock strata dip below the floor. At the arrow, Dodo Creek is diverted westwards along a spillway parallel to the Mackenzie Valley. <u>Upper right</u> – looking across the spillway sector from a tributary canyon in the Breccia. The Hume limestones form the prominent cliffs in the rear and the Mackenzie Valley lies beyond. <u>Lower right</u> – Dodo Creek in its spillway sector. It leaves via one final abrupt turn North (to the left) and enters the Valley.

Morphological map of Lower Dodo Canyon and Carcajou Canyon

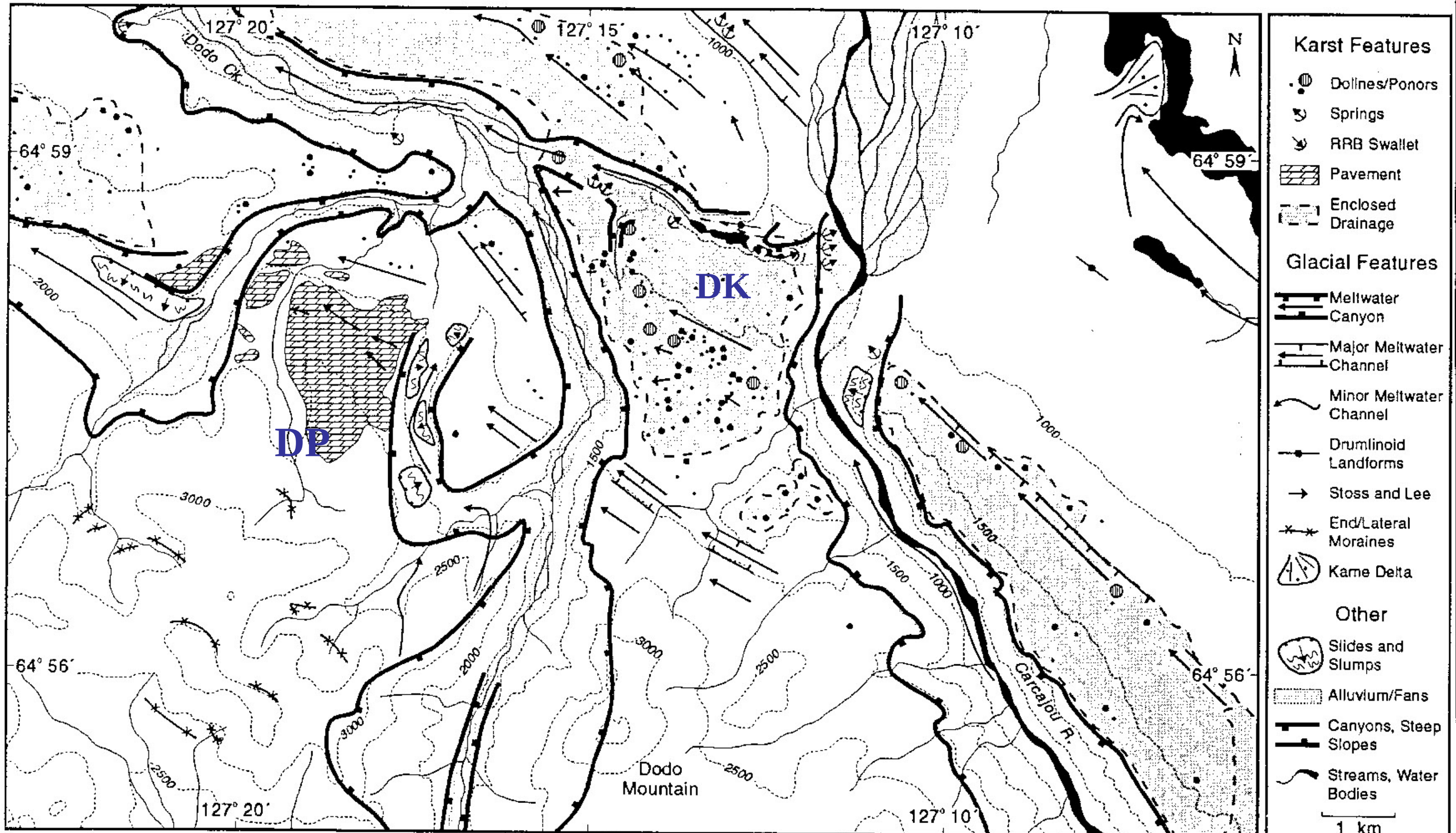


Figure 7.7: General geomorphology of the Dodo Canyon Site. Several canyon features have orientations that are parallel to the mountain front, others occupy anomalous positions that cut across older drainage. This distribution is related to the diversion of mountain streams and the routing of meltwaters by Laurentide Ice near the mountain front. Streamlined features indicate an ESE-WNW movement of Laurentide Ice. In the high range west of Dodo Mountain both montane and Laurentide moraines are recognized. Preliminary interpretation favours a minor montane advance following the Laurentide Katherine Creek maximum. The karst features shown are springs, dolines, pavement, and areas of enclosed drainage (shaded). The pavement is located on the Mount Kindle Formation, the majority of the doline karst is on the Bear Rock and Hume Formations. The size of the doline markers represents the approximate minimum dimension of their immediate catchment, divided into: small (<10 m), intermediate (25 m), or large basins (>50 m). At this scale not all karst input or output features are depicted.

Dodo Pavements (DP) and the Drape Karst (DK) above lower Dodo Canyon are two of the greatest suites of karst landforms in the Norman Wells region. Map by Jim Hamilton.

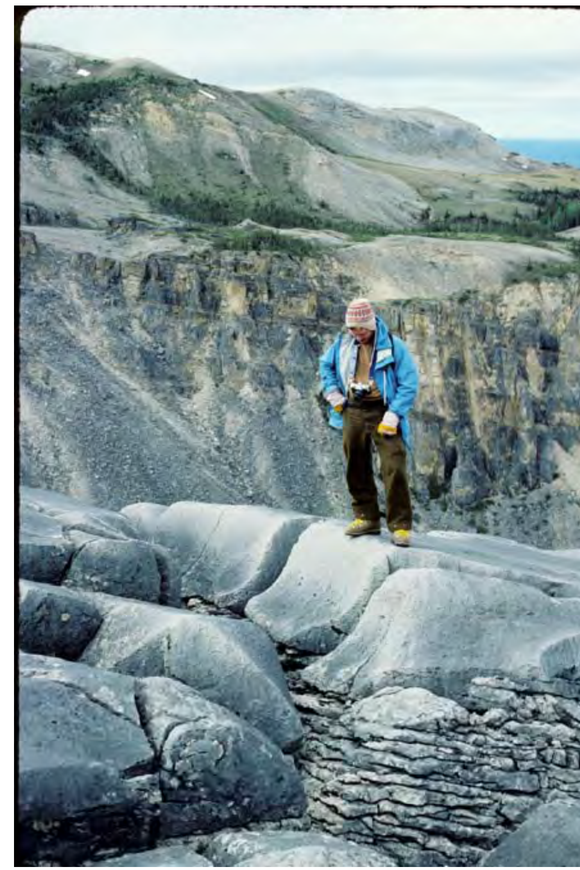
The Dodo West Karst Pavements

These two pictures both show the upper beds of the resistant Mt Kindle dolomites. On left – on the never-glaciated Plains of Abraham, where periglacial frost shatter processes predominate. On right – on Dodo West where the last Laurentide glacier scoured all loose debris away, exposing fresh bedrock to karst solutional attack.

__Left__ – a general view southwards across the pavements, with Dodo Mountain in the rear on the other side of Dodo Canyon.

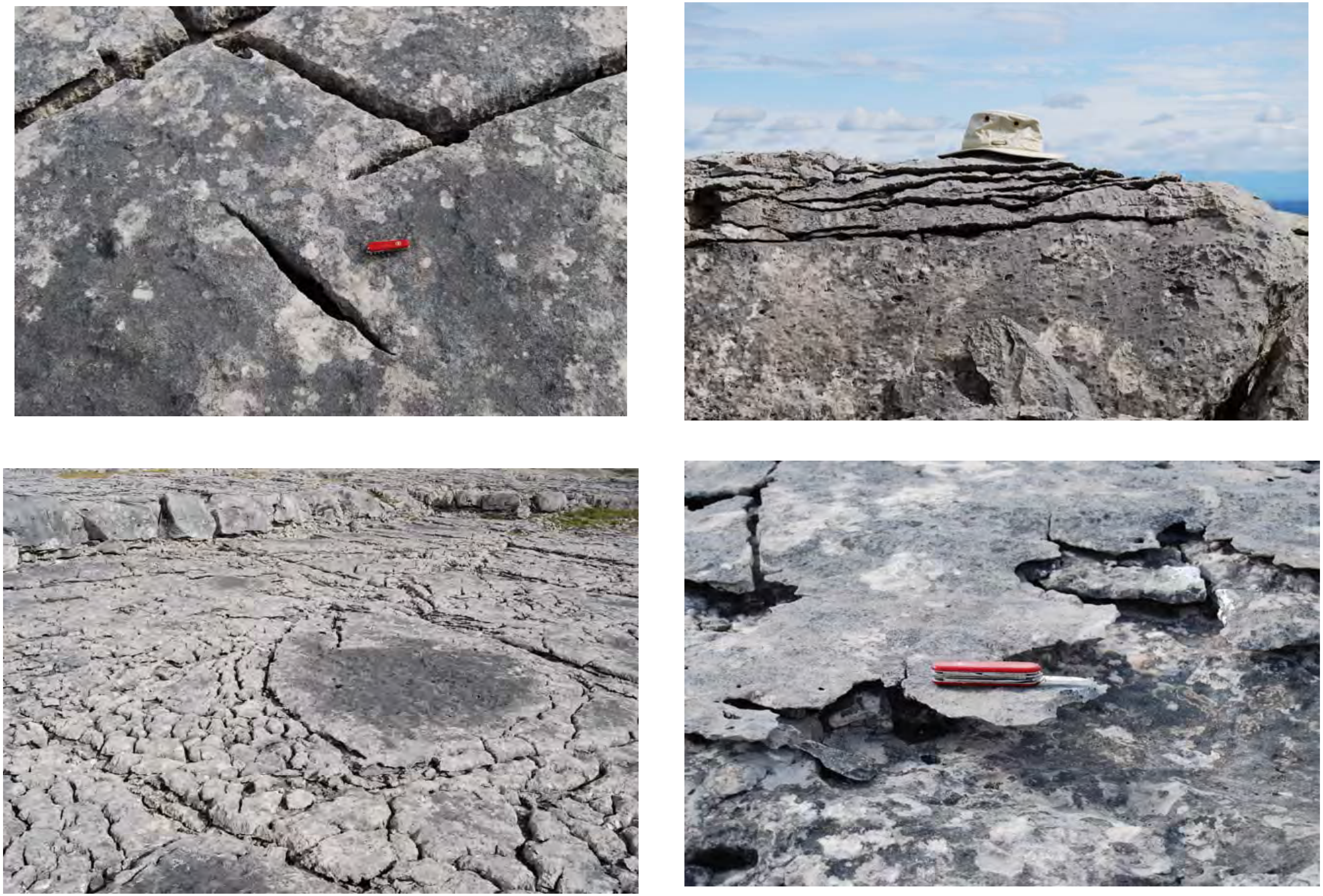
__Right__ – view northwards down the dipping pavements to Carcajou River and the Mackenzie Valley in the rear.

The Mt Kindle dolomites were 'cyclic' deposits of thick and strong beds, succeeded by weak thin beds like meat in a sandwich (<u>above</u>). Glacier ice bulldozed the rock away along the weaker beds, creating a staircase-like topography (<u>upper right</u>). Each strong bed surface that was exposed tends to have slightly different properties with the consequence that the detailed solutional landforms (karren) are never quite alike on any two beds.



Along the edges of the pavement terrain, glaciers and the early post-glacial spillway streams made some shallow entrenchments and created isolated pinnacles (<u>above</u>). <u>On right</u> – Dr Jim Hamilton stands by a 'P form', a subglacial channel dissolved into the dolomite by a short-lived stream. Note the contrast between the massive bed of the channel walls and the weak beds below it.

Some dolomite beds are rich in fossils which are silicified (the original calcite is replaced by silica, which is much less soluble). The fossils now stand proud above the dolomite surface and some frame micro solution pits where soluble dolomite filling the fossil interior has been removed



Some differing patterns on the dolomite pavement. Even the strong beds may be fractured by frost action and reduced to blades or rubble.

Twelve thousand years or more after the glacier receded frost has begun to break up the karren and vegetation is establishing a hold. Only a few scattered Shield erratics attest to the presence of the Laurentide Ice Sheet here.

Looking North across the pavements with the Breccia karst beyond and the confluence of Dodo Creek and Carcajou River in the background. The West Dodo dolomite karst pavements are amongst the finest known anywhere in the arctic regions.

The Dodo Breccia Drape Karst

Between Dodo Canyon and Carcajou Canyon the Bear Rock Breccia is dissected by karst processes into a fantastical landscape unknown in any other part of the world. It was its dramatic appearance on air photos that first drew the author to reconnoitre the regional geomorphology in 1983. Meltwaters from the Laurentide Ice Sheet and then thousands of years of rain and snow melt have scoured corridors and sinkholes into the Breccia, destroying its softer parts and leaving more resistant, hardened surface crusts such as the Landry Member draped on ridges and sliding into the solutional depressions, as shown here.

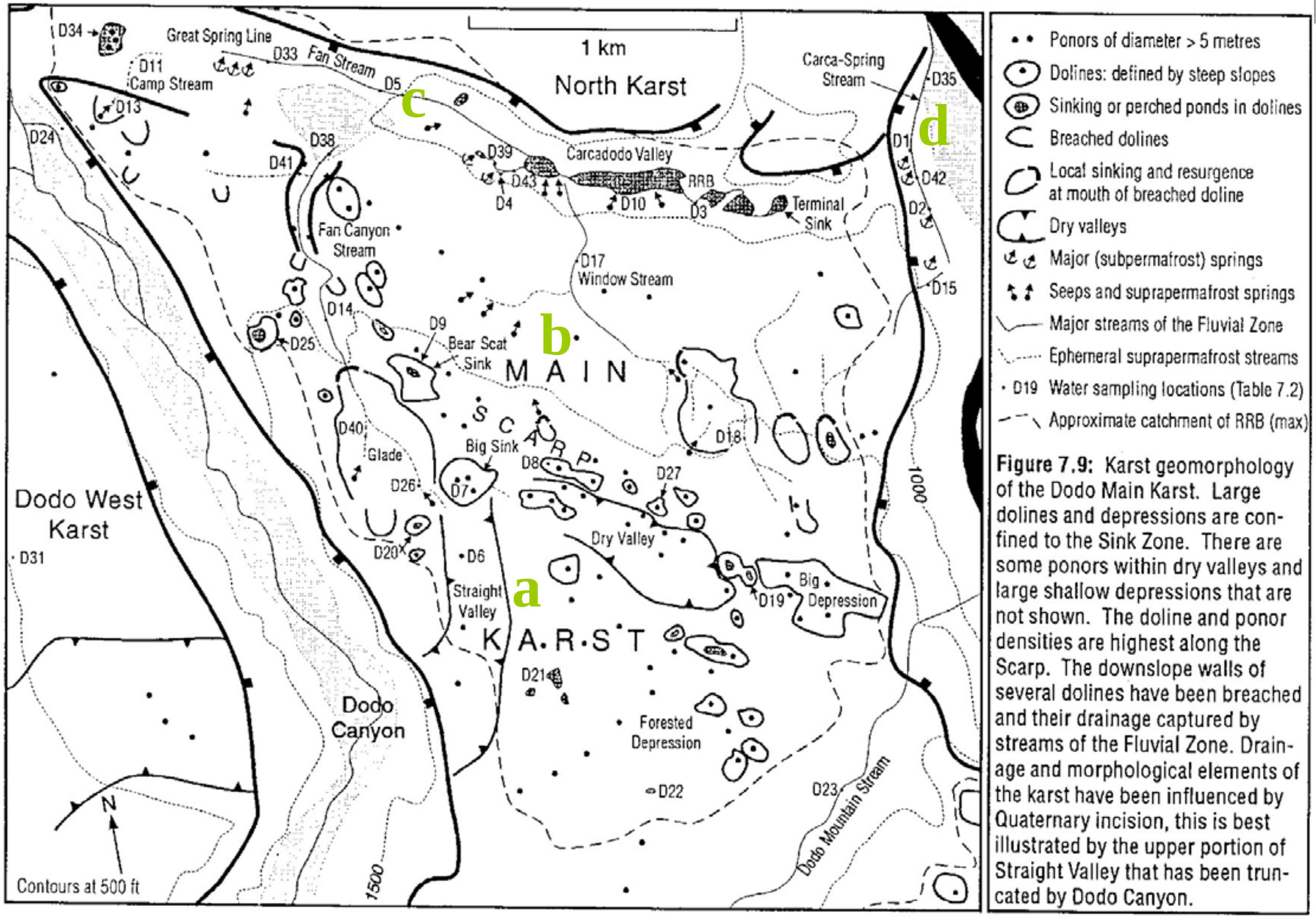


Figure 7.9: Karst geomorphology of the Dodo Main Karst. Large dolines and depressions are confined to the Sink Zone. There are some ponors within dry valleys and large shallow depressions that are not shown. The doline and ponor densities are highest along the Scarp. The downslope walls of several dolines have been breached and their drainage captured by streams of the Fluvial Zone. Drainage and morphological elements of the karst have been influenced by Quaternary incision, this is best illustrated by the upper portion of Straight Valley that has been truncated by Dodo Canyon.

This was Jim Hamilton's principal study area for the PhD thesis (see Appendix D). His map here divides the karst into three broadly parallel belts: (a) upslope, a belt of comparatively weak scour by Laurentide meltwaters, with dry valleys and scattered sinkholes; (b) a central, more dissected belt of sinkholes; (c) Carcadodo Valley, a part of The Great Spillway (below), where much of the water sinking in (a) and (b) returns as springs, only to sink again at the east end of the Valley and rise at (d) as freshwater and salt springs in Carcajou Canyon.

A general view of belt (a) and part of (b) with disordered dry valleys and scattered sinkholes.

Further scenes in the upper belts. Lower photos show an example of hardened breccia crust tipped on end and sliding downslope, and some of the superb patterned ground, both evidences of the vigour of periglacial processes on the Breccia.

This aerial photograph of a very beautiful sinkhole with its pond perched on permafrost but leaking slowly into the groundwater aquifer underneath has delighted fellow geomorphologists worldwide when they have seen it. It is an ideal example of periglacial karst.

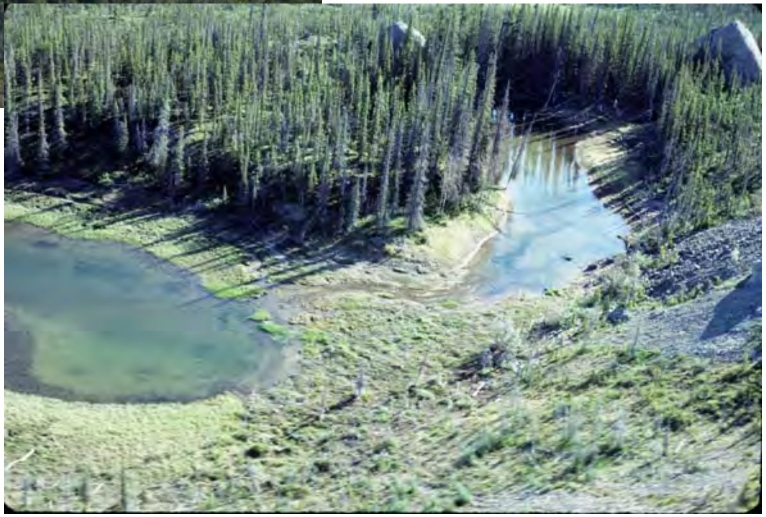
Other ponded sinkholes in belt (b). That in the lower photographs is perched on the rim of Dodo Canyon but does not drain into it, leaking into the general Breccia aquifer instead. It is a testimony to the blocking powers of the permafrost here.

<u>Above</u> – this view of the lower part of belt (b) captures something of the chaotic nature of its dissolve-and-drape topography. In the right foreground a spring from within the permafrost ('intrapermafrost flow') has carved a small canyon. It evidently flows until the early winter because there is a substantial buildup of ice where it emerges (an icing) that survives well into the summer.

A general view from east to west along the 'Carcadodo Valley'. The aircraft is over the steep drop off into Carcajou Canyon. This was an important section of The Great Spillway at the end of the last glaciation, when meltwater flowed along it from east to west. Today its stream is fed by springs from the Drape Karst belts (on left) and flows from west to east until sinking again in left centre.

<u>Above left</u> – view down into Carcadodo Valley from belt (b).
<u>Above right</u> – view from the east. The delta fan is debris from the icing spring shown on page 205.

<u>Below</u> – the Hume Limestone Formation forms the north wall of the Valley, seen here looking east towards Carcajou Canyon.



<u>Above</u> – the Carcadodo stream flowing east to its sinkpoint (arrow); July 2007. In rear, the Carcajou River flows from the mouth of its canyon. <u>On right</u> – a detail from the 1989 field study season; the sinkhole ponds were very similar in extent to 2007.

<u>Above left</u> – approaching the Carcadodo stream sink in July 2007.
<u>Above right</u> – conducting a dye trace with fluorescein at the sink in 1989. As expected, the groundwater flowed to springs in Carcajou Canyon.
<u>Right</u> – Jim Hamilton at the water level recorder set up in Carcadodo Valley in 1989 to measure the flow of the karst stream. Mean discharge was about 150 l/s.
Wild orchids are abundant around the stream sink.

Three views of springs at the mouth of Carcajou Canyon. <u>Above left</u> – the arrow shows the stream sink in Carcadodo Valley. The springs are in the foreground. <u>Above right</u> – the flow from the springs is bright but peaty, readily distinguished from the turbid, silty water of Carcajou River.
<u>Below</u> – measuring temperature and conductivity in the springs. They were at 10.7 C and carrying about 4000 mg/l of salt, plus dissolved dolomite and gypsum.

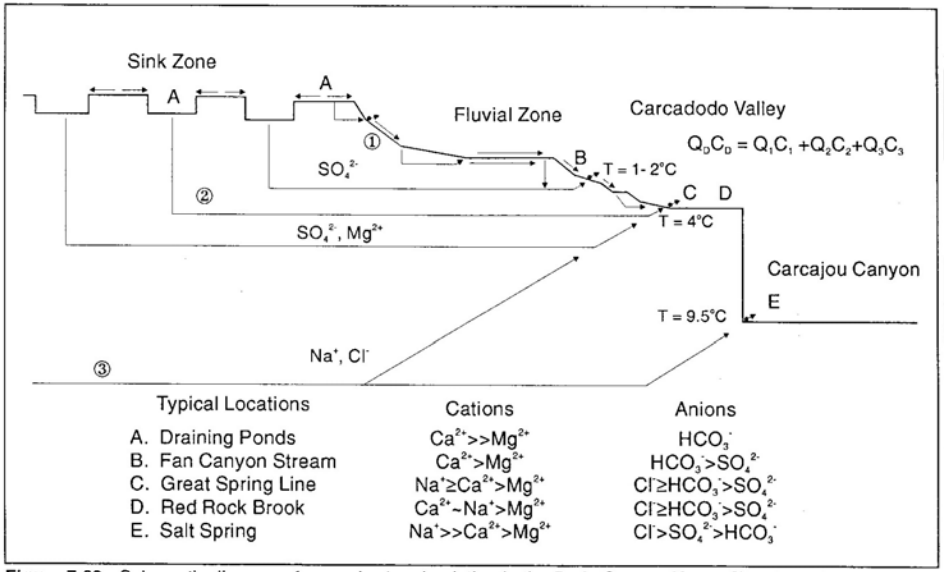


Figure 7.32: Schematic diagram of groundwater circulation in the Dodo Canyon Karst. The figure is not to scale. Changes in ion abundance are indicated for five locations that are typical of the data set. Spring temperatures are shown for the Fluvial Zone, Carcadodo Valley, and along Carca-Spring Stream. Red Rock Brook takes flow from shallow, intermediate, and deep groundwater components. The latter has high concentrations of Na^+ and Cl^-. Much of the SO_4^{2-} and Mg^{2+} is from the intermediate Bear Rock and Mount Kindle Formations aquifer.

<u>Above</u> – Jim Hamilton's model for the chemistry of karst groundwaters in the Breccia. Type (1), intrapermafrost, water is dissolving chiefly gypsum. Type (2) water reaches the base of the permafrost and dissolves both gypsum and dolomite. It takes 40 – 50 days to travel to the springs in Carcadodo Valley. Type (3) water is warmed by long distance, deep flow into the salt of the Saline River Formation. <u>On right</u> – salt-tolerant lichens and slimes in a young salt spring.

(D) The Great Spillway

In the closing stages of the last glaciation the edge of the Laurentide Ice Sheet overlapped the E-W trending front of the Mackenzie Mountains in the area west of Norman Wells, burying their first few hundred metres. The Ice Sheet can be envisioned as a giant upturned saucer. Meltwater pouring off of it flowed westwards as a river, carving a deep channel that was just inside the mountains and parallel to their front. It was abandoned when the Ice Sheet retreated further.
In postglacial times, rivers flowing northward from the heart of the mountains to the Valley were locally diverted westwards along the Spillway for some km before discovering escape routes into the Valley; the lowest section of Dodo Canyon is an example. The sections of the Spillway between these chance invading creeks remain abandoned. As a result, the Spillway today presents a spectacular variety of landforms (river, karst and mass wasting) in rapid succession. It is a fitting conclusion for the Canol HeritageTrail International Geopark that is being recommended in this report.
(<u>Above</u> – Katherine Creek is an underfit stream in the Great Spillway west of the Dodo Pavements).

After approaching within three kms of the Mackenzie Valley the Carcajou River abruptly turns west for 24 km along the Spillway before finally entering the Valley.
<u>Above</u> – the River flowing in the easterly section of the Spillway, with the canyon walls steadily rising.
<u>Right</u> – in the deepest parts of Carcajou Canyon the walls are more than 500 metres in height. The strata here are the Mt Kindle dolomites with the Bear Rock breccia above them.

<u>Above left</u> –the contact between the Mt Kindle resistant dolomite is seen clearly in the Canyon walls. <u>Above right</u> – the western end of Carcajou Canyon.

<u>Right</u> – the Canyon mouth with limestones of the Hume Formation seen dipping under the weak, younger sediments of the Mackenzie Valley.

The second segment of the Great Spillway is now the Carcadodo Valley, fed by local springs from theDrape Karst that drain eastwards before sinking underground again. The valley is seen here in wet conditions in 1983. The prominent cliffs are in the Hume Fm.

<u>Left</u> – the third segment of the Great Spillway is followed by Dodo Creek in the lowest section of its canyon, shown here where the creek makes its final turn north into the Mackenzie Valley.

<u>Right</u> – the fourth segment is one of the most spectacular, a broad dry canyon carved into the Mt Kindle dolomites. It is seen looking west (downstream when the spillway was active) from a viewpoint on the edge of the Dodo Pavements. A massive landslide is seen behind the figure. Cliffs in the distance are the southern wall of the Katherine Creek segment of the spillway.

The landslide is technically a ‘rotational landslip’ in which the rock fails as successive solid slices that rotate (tilt) backwards as they slide down. Here there were seven successive slips, forming a staircase of treads and risers. This landslide was caused by undercutting during the late stages of the Spillway floods. Slides on this scale are extremely rare in strong rocks such as the Mt Kindle dolomites. This is the finest example I have seen anywhere in dolomites.

<u>Above</u> – Katherine Creek entering the Great Spillway and entrenching a channel in the glacial outwash sediments in its floor. The unbroken floor is seen in the rear and the Dodo Pavements on the plateau behind. <u>Right</u> – two views lower in the Katherine Creek segment of the Spillway. It is cut in the Bear Rock breccia with the top of the Mt Kindle dolomites seen from place to place. The Creek is diverted westwards along the Spillway for eight km before escaping north into the Mackenzie Valley.

From Katherine Creek the Spillway extends westwards for eight km to "The Great Fan" where it is breached temporarily so that its form is lost.
It is carved primarily in the Breccia with uppermost beds of the Mt Kindle dolomites occasionally seen.

<u>Above</u> – after Katherine Creek the Spillway bifurcates for a few kms, creating some particularly complex topography.

<u>On right</u> – for the final few km it becomes a single feature again.

The Mackenzie Mountain front rises very steeply on the south side of the Spillway so that its southern flank is dissected by many small canyons and lesser ravines.

The more strongly cemented Landry Member of the Bear Rock Fm is seen here capping or draped over more erodible dolomitic breccia underneath. It contributes to the 'sci fi' fantastical nature of the scenery here.

On the ground towards the western end of the Great Spillway. The very steep front of the Mackenzie Mountains is seen on the left, a source of abundant debris for building fans. The Landry Member is the ledge-forming stronger unit in the Breccia on the right.

<u>**Above left**</u> **– broken pavement at the top of the Mt Kindle dolomite.**
<u>**Above right**</u> **– the remnants of a cave in the Breccia.**

<u>**Right**</u> **– typical pinnacle development in this part of the Spillway.**




Close-ups of some pinnacles in the Breccia and the solifluctual processes at work on the detritus.

In the final couple of km the Great Spillway becomes overwhelmed with fans of debris from the Mackenzie Mountains front. It is a scene of extremely vigorous geomorphic activity today.

This spectacular fan consists of a sequence of lobate debris flows building out in front of or piling on top of one another, from a source in a raw, young ravine. It was possibly created by pulses within one great erosional event. The rocks are from the Breccia, demonstrating how easily erodible this is during intense storms.

As the name I have given it suggests "The Great Fan" is the largest in the region. It debouches from an unnamed canyon. Its apex is at N 65 04', W 127 40' at an elevation of approximately 375 m above sea level. It is five km in length and three in width, draining into Grafe River. It buries the Great Spillway here. The abundant debris is chiefly from the Bear Rock Breccia.

Discussion and Recommendations – Geomorphic Landscapes from the Plains of Abraham to Carcajou, Dodo and Katherine Canyons and the Great Fan.

Treated as individual sites of interest, (1) the Plains of Abraham (page 160, in particular the steephead springs, p. 167), Pyramid Lake Polje (p. 169), Dodo Dry Canyon (p. 173), Dodo Canyon (p.180), the Dodo West Karst Pavements (p.191), the Dodo Breccia Drape Karst (p. 199), the Great Fan landslide (p. 217) and the western Great Spillway and Fan (p.222) are all worthy of protection as karst or other geomorphic and geologic features of exceptional quality and significance. However, as noted on page 157 introducing this final part of the Norman Wells regional survey, the majority of these outstanding features are on the Canol Heritage Trail or very close to it. As a consequence

(1) It is recommended that consideration be given to placing all of these sites, plus the Falls of the Little Keele River, Carcajou and Katherine canyons, within one protected area linked together by the Heritage Trail between the mouth of Dodo Canyon and the southern end of the Plains of Abraham, and

(2) Because of the outstanding quality and universal significance of this combined protected area it be vigorously promoted nationally and internationally for recognition as a UNESCO International Geopark, and further

(3) That consideration be given to setting the boundaries of Geopark such that the Bonus Lake Scablands Karst (p.135) and Moraine Polje (p.146) can be included within it.

Outline of the UNESCO International Geoparks Programme

GEOPARKS – *Promoting Earth Heritage, Sustaining Local Communities*

Global Network of National Geoparks - *a landscape approach for geological heritage conservation, research and sustainable development*

Introduction

Geology and landscape have profoundly influenced society, civilization, and the cultural diversity of our planet but until recently, no international recognition of geological heritage sites of national or regional importance, and no international convention specifically on geological heritage have existed. The initiative of UNESCO to support Geoparks responds to the strong need expressed by numerous countries for an international framework to enhance the value of the Earth's heritage, it's landscapes and geological formations, which are key witnesses to the history of life.

Pursuant the decision of its Executive Board in June 2001 (161 EX/Decisions, 3.3.1) UNESCO has been invited *"to support ad hoc efforts with Member States as appropriate"* to promote territories or natural parks having special geological features. National Geopark initiatives, which seek UNESCO's assistance should integrate the preservation of significant examples of geological heritage in a strategy for regional sustainable socio-economic and cultural development, safeguarding the environment.

The present document provides guidelines for developing National Geoparks under the assistance of UNESCO for the inclusion in a Global Network. The applicant is asked to respect the terms of the present guidelines. An independent expert group will refer to these guidelines when assessing proposals for the Global Network.

The protection and sustainable development of geological heritage and geodiversity through Geoparks initiatives, contributes to the objectives of Agenda 21, the Agenda of Science for Environment and Development into the twenty-first century adopted by the United Nations Conference on Environment and Development (UNCED, Rio de Janeiro, 1992) and which was reconfirmed by the World Summit on Sustainable Development 2002 in Johannesburg. The Geoparks initiative adds a new dimension to the 1972 Convention concerning the Protection of the World Cultural and Natural Heritage by highlighting the potential for interaction between socio-economic and cultural development and conservation of the natural environment.

The Global Network of National Geoparks operates in close synergy with UNESCO's World Heritage Centre, the Man and the Biosphere (MAB) World Network of Biosphere Reserves, national and international undertakings and non-governmental organizations active in geological heritage conservation. For national Geoparks in Europe, UNESCO has established a privileged partnership with the *European Geoparks Network (EGN)* since 2001. As a result, the EGN acts as the Global Geoparks Network for Europe. UNESCO recommends the creation of similar regional Networks, reflecting local conditions, elsewhere in the world. Networking among Geoparks is an important component of the Global Network of National Geoparks. UNESCO encourages any form of cooperation especially in the fields of education, management, tourism, sustainable development, regional planning among Network members.

Part I - Criteria

1. Size and setting

- A Geopark seeking to become member of the Global Network of National Geoparks is an area with well-defined limits and a large enough surface area for it to serve local economic and cultural development (mainly through tourism). It comprises a number of internationally important geological heritage sites on any scale, or a mosaic of geological entities of special scientific importance, rarity or beauty. These features are representative of a region's geological history and the events and processes that formed it.

- A 'Geopark' is a geographical area where geological heritage sites are part of a holistic concept of protection, education and sustainable development. The Geopark should take into account the whole geographical setting of the region, and shall not solely include sites of geological significance. Non-geological themes are an integrated part of it, especially when their relation to landscape and geology can be demonstrated to the visitors. For this reason, it is necessary to include also sites of ecological, archaeological, historical or cultural value. In many societies, natural, cultural and social history are inextricably linked and thus cannot be separated.

- If the area of a Geopark is identical to or partly or wholly overlaps with an area already inscribed, for example, on the World Heritage List or registered as a Biosphere Reserve of the Man and the Biosphere Programme of UNESCO, it is necessary to obtain prior clearance from the appropriate bodies of the said initiatives before submitting the application.

2. Management and local involvement

- Prerequisite to any successful Geopark proposal is the establishment of a management body and plan. The presence of impressive and internationally significant geological outcrops alone is not sufficient. The geological features inside the Geopark area must be accessible to visitors, are linked to one another and safeguarded in a formally managed park-type situation. The Geopark is run by a designated local authority or several authorities having an adequate management infrastructure, qualified personal and adequate financial support.

- The establishment of a Geopark is a bottom-up process. It should be based on a strong multi task-force concept and political will with long-term financial support, and professional management structures, which adopts its own territorial policy for sustainable regional socio-economic and cultural development. Success can only be achieved through strong local involvement. The initiative to create a Geopark must therefore come from local communities/authorities with a strong commitment to developing and implementing a management plan that meets the economic needs of the local population whilst protecting the landscape in which they live. Nevertheless, it needs to be endorsed at national level by the National Commission to UNESCO.

- A Geopark shall provide organizational arrangements to involve public authorities, local communities, private interests, and both research and educational bodies in the design and running of the park and its regional economic and cultural development plan and activities. This co-operation shall stimulate discussion and encourage partnerships between the different groups having a vested interest in the area; it shall motivate and mobilise local authorities and the local population.

- The identity of a Geopark must be clearly visible for visitors. This is achieved through a strong public relations concept including common branding/labelling of the sites belonging the the Geopark, the publications and all activities taking place there.

- Sustainable tourism and other economic activities within a Geopark can only be successful if carried out in cooperation with local communities. Tourism activities have to

Etc.

Excerpted from 'Guidelines and Criteria for National Geoparks seeking UNESCO's assistance to join the Global Geoparks Network' dated January 2007

The UNESCO World Heritage Programme

Arrows indicate criteria for WH status that the Canol Heritage protected area will meet.

Cultural criteria

- **I**. "to represent a masterpiece of human creative genius";
- **II**. "to exhibit an important interchange of human values, over a span of time or within a cultural area of the world, on developments in architecture or technology, monumental arts, town-planning or landscape design";
- **III**. "to bear a unique or at least exceptional testimony to a cultural tradition or to a civilization which is living or which has disappeared";
- **IV**. "to be an outstanding example of a type of building, architectural or technological ensemble or landscape which illustrates (a) significant stage(s) in human history";
- **V**. "to be an outstanding example of a traditional human settlement, land-use, or sea-use which is representative of a culture (or cultures), or human interaction with the environment especially when it has become vulnerable under the impact of irreversible change";
- **VI**. "to be directly or tangibly associated with events or living traditions, with ideas, or with beliefs, with artistic and literary works of outstanding universal significance. (The Committee considers that this criterion should preferably be used in conjunction with other criteria)";

Natural criteria

- **VII**. "to contain superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance";
- **VIII**. "to be outstanding examples representing major stages of earth's history, including the record of life, significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic features";
- ? **IX**. "to be outstanding examples representing significant on-going ecological and biological processes in the evolution and development of terrestrial, fresh water, coastal and marine ecosystems and communities of plants and animals";
- **X**. "to contain the most important and significant natural habitats for in-site conservation of biological diversity, including those containing threatened species of outstanding universal value from the point of view of science or conservation."

Statistics

See also: Table of World Heritage Sites based on State Parties

There are currently 851 World Heritage Sites located in 142 State Parties. Of these, 660 are cultural, 166 are natural and 25 are mixed properties. Further site classification includes the classification of the State Parties among five geographic zones: Africa, Arab States (composed of northern Africa and the Middle East), Asia-Pacific (includes Australia and Oceania), Europe and North America (specifically, USA and Canada), and Latin America and the Caribbean.

Note that Russia and the Caucasus States are classified as belonging to the Europe and North America zone.

231 A long-term plan to seek UNESCO World Heritage status for the proposed Canol Heritage Geopark?

UNESCO World Heritage status as a Cultural or Natural site of outstanding significance is the highest level of recognition that a given national park or similar site can achieve under the aegis of UNESCO at the present time. It has been and is highly sought after by many nations, including Canada, since its inception in 1977 because of its importance in international tourism.

I, the author of this Report, have accumulated substantial experience in (a) preparing the national cases for natural sites for evaluation by UNESCO or the International Union for the Conservation of Nature (IUCN) as its proxy, and (b) making site evaluations for UNESCO/IUCN. On behalf of national parties I played a part in gaining WH status for South Nahanni River National Park Reserve and the Rocky Mountain National Parks in Canada, Mammoth Cave and Carlsbad Caverns NPs in the United States, Mulu NP (Malaysia), the Aggtelek/Slovak Caves property (Hungary/Slovakia), Jeju Island Volcanic Landforms (South Korea), and the South China Karst (three properties in PR China). For UNESCO and/or IUCN I have evaluated proposals from Chile, Cuba, France and Germany and am currently taking part in a global assessment of the adequacy of regional representation of karstic properties on the WH list.

Based on this experience <u>it is my professional opinion that a Canol Heritage Geopark as outlined above would have an excellent chance of achieving World Heritage status because it is of outstanding quality and significance under Criteria VII and VII (page 230) and probably under Criterion IX also; (recognition is needed under only one criterion but two are now preferred).</u>

Further, because of its intimate association with the Canol Road it is to be anticipated that a proposal would receive very strong support from the United States.

The first essential steps here will be to coordinate with Parks Canada and get the proposed Canol Heritage Geopark placed on Canada's 'Tentative List' for UNESCO.

International geopark criteria

Report upon a Survey of Karst Landforms

around Norman Wells, Northwest Territories

for the Protected Areas Department
Environment and Natural Resources
Government of the Northwest Territories

by

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References

Aitken, J.D. and Cook, D.G. 1969. Lac Belot (Geology), District of Mackenzie. Geological Survey of Canada, Preliminary Series map 6-1969.

Aitken, J.D. and Cook, D.G 1974. Carcajou Canyon map-area, District of Mackenzie, Northwest Territories. Geological Survey of Canada, Paper 74-3.

Cook, D.G. and Aitken, J.D. 1971. Geology, Colville Lake map-area and partof Coppermine map-area, Northwest Territories. Geological Survey of Canada, Paper 70-12.

Cook, D.G. and Aitken, J.D. 1975. Geology, Norman Wells (96E) and Mahomy lake (96F), District of Mackenzie. Geological Survey of Canada, Open File 304.

Cook, D.G. and Aitken, J.D. 1976. Geology, Blackwater Lake (96B) and Fort Norman (96C), District of Mackenzie. Geological Survey of Canada, Open File 402.

Douglas, R.J.W and Norris, A.W. 1974. Geology, Great Slave Lake, District of Mackenzie. Geological Survey of Canada, Map 1370A. Scale 1:500,000.

Duk-Rodkin, A. and Hughes, O.L 1991. Age relations of Laurentide and montane glaciations, Mackenzie Mountains, Northwest territories. Geographie physique et Quaternaire, 45, 75-90.

Duk-Rodkin, A. and Hughes, O.L. 2002. Surficial Geology, Carcajou Canyon, Northwest Territories. Geological Survey of Canada, map 1988A, scale 1:250,000.

Ford, D.C. 1982. Karst groundwater activity in the modern permafrost regions of Canada, in R. LaFleur (Ed.) *Groundwater Weathering in Geomorphology*, George Allen and Unwin, London, 1984, pp. 340-350.

Ford, D.C. 1987. Effects of Glaciations and Permafrost upon the Development of Karst in Canada. *Earth Surface Processes and Landforms*, 12(5), pp. 507-522.

Ford D.C. 1992. Karst et Glaciation, invited chapter in J.-N. Salomon and R. Maire (Eds.) *Karsts et Evolutions Climatiques*, Presses Universitaires de Bordeaux, pp. 249-266.

Ford, D.C. 1997. Principal features of evaporite karst in Canada. *Carbonates and Evaporites*, 12(1), pp. 15-23.

Ford, D.C. 1997. Karst in a Cold Climate. in McCann, S.B. and Ford, D.C. (eds.) *Geomorphology sans Frontieres*, London, John Wiley & Sons Ltd., pp. 153-179.

Ford, D.C. 2004. Bear Rock Karst, Canada. in John Gunn (Editor) *Encyclopedia of Caves and Karst Science*. New York, Fitzroy Dearborn; pages 137-138.

Ford, D.C. 2004. Solution Breccias. in John Gunn (Editor) *Encyclopedia of Caves and Karst Science*. New York, Fitzroy Dearborn; pages 660-661.

Ford, D.C. and Quinlan, J.F. 1973. Theme and Resource Inventory Study of the Karst Regions of Canada. Parks Canada, Contract 72-32A. 112 p.

Ford, D. & Williams, P. (2007) *Karst Hydrogeology and Geomorphology*. Chichester: John Wiley & Sons, Ltd. xiii, 563 p.

Hamilton, J.P. 1995. Karst Geomorphology and Hydrogeology of the Northeastern Mackenzie Mountains, District of Mackenzie, N.W.T., Canada. PhD thesis, McMaster University. xvi, 532 p.

Hamilton, J. and Ford. D.C. 2002 Karst geomorphology and hydrogeology of the Bear Rock formation – a remarkable dolostone and gypsum megabreccia in the continuous permafrost zone of Northwest Territories, Canada. Carbonates and Evaporites, 17(2);

Hamilton, J. and Ford, D.C. 2001. Karst geomorphology and Hydrogeology of the Bear Rock Formation, a Remarkable Dolostone and Gypsum Megabreccia in the Continuous Permafrost Zone of the Northwest Territories, Canada. In Gunay, G., Johnson, K.S., Ford, D.C. and Johnson, A.I. (editors). *Present state and future trends of Karst studies*. Proceedings of the 6th International Symposium and Field Seminar, Marmaris, Turkey. Paris, UNESCO IHP-V Technical Documents in Hydrology, No. 49. pp. 63-66.

Heginbottom, J.A. and Radburn, L.K. 1992. Permafrost and ground cie condtions of northwestern Canada. Geological Survey of Canada, Map 1691A, scale 1:1,000,000.

Lundberg, J. and Ford, D.C. 1994. Canadian Landform Examples: Limestone and Dolomite Pavements, with an example from Dodo Creek, Mackenzie Mountains, NWT. *The Canadian Geographer*, 38(3), pp. 271-5.

Meijer Drees, N.C. 1986. Evaporitic deposits of western Canada. Geological Survey of Canada, Paper 85-20.

Meijer Drees, N.C. 1993. The Devonian succession in the subsurface of the Great Slave and Great Bear Plains.. Geological Survey of Canada, Bulletin 393.

Norford, B.S. and Macqueen, R.W. 1975. Lower Paleozoic Franklin Mountain and Mount Kindle Formations, District of Mackenzie; their type sections and regional development. Geological Survey of Canada, Paper 74-34.

Pugh, D.C. 1993.Subsurface geology of the pre-Mesozoic strata, Great Bear River map area, District of Mackenzie. Geological Survey of Canada, Memoir 430.

Van Everdingen, R.O. 1978. Frost mounds at Bear Rock, near Fort Norman, Northwest Territories, 1975-1976. Canadian Journal of Earth Sciences, 15(2); 263-276.

Van Everdingen, R.O. 1981. Morphology, Hydrology and Hydrochemistry of Karst in Permafrost Terrain near Great Bear Lake, Nortyhwest Territories. National Hydrology research Institute, NHRI Paper No. 11. 53 p.

Van Everdingen, R.O. and Banner, J.A. Use of long-term automatic time lapse photography to measure the growth of frost blisters. Canadian Journal of Earth Sciences, 16(8); 1632-1635.

Van Everdingen, R.O. and Krouse, H.R. 1977a. Sulfur isotope geochemistry of springs in the Franklin Mountains, N.W.T., Canada. Proceedings, Second International Symposium on Water-Rock Interactions,Strasbourg; vol 1, pp. 134-145.

Van Everdingen, R.O. and Krouse, H.R. 1977b. Stratgraphic differentiation by sulphur isotopes between Upper Cambrian and Lower Devonian gypsum-bearing units, District of Mackenzie, N.W.T., Canada.. Canadian Journal of Earth Sciences, 14(12); 2790-2796

Van Everdingen, R.O., Michel, F.A., Krouse, H.R. and Fritz, P. 1978. Hydrochemical and isotope analysis of groundwater flow systems, Franklin Mountains, District of Mackenzie, Northwest Territories, Canada. Proceedings, National Hydrogeological Conference, International Association of Hydrogeologists, CanadianNational Chapter; pp. 165-178.

Vincent, J.S. 1989. Quaternary geology of the northern Canadian Interior Plains. in Fulton, R.J. (editor) Quaternary Geology of Canada and Greenland, Geology of Canada, No. 1; Geological Survey of Canada, pp.100-137.