KARST DEVELOPMENT IN THE GLACIATED AND PERMAFROSTREGIONS OF THE NORTHWEST TERRITORIES, CANADA

Derek Ford
School of Geography and Earth Sciences, McMaster University, Canada dford@mcmaster.ca

The Northwest Territories of Canada are ~1.2 million km^2 in area and appear to contain a greater extent and diversity of karst landforms than has been described in any other region of the Arctic or sub-Arctic. The Mackenzie River drains most of the area. West of the River, the Mackenzie Mountains contain spectacular highland karsts such as Nahanni (Lat. 62° N) and Canol Road (Lat. 65° N) that the author has described at previous International Speleological Congresses. This paper summarizes samples of the mountain and lowland karst between Lats. 64–67° N that are located east of the River. The Franklin Mountains there are east-facing cuestas created by over-thrusting from the west. Maximum elevations are ~1,000 m a.s.l., diminishing eastwards where the cuestas are replaced by undeformed plateaus of dolomite at 300–400 m asl that overlook Great Bear Lake. In contrast to the Mackenzie Mountains (which are generally higher) all of this terrain was covered repeatedly by Laurentide Continental glacier ice flowing from the east and southeast. The thickness of the last ice sheet was >1,200 m. It receded c.10,000 years ago. Today permafrost is mapped as "widespread but discontinuous" below 350 m a.s.l. throughout the region, and "continuous" above that elevation. The vegetation is mixed taiga and wetlands at lower elevations, becoming tundra higher up. Access is via Norman Wells (population 1,200), a river port at 65° 37'N, 126° 48'W, 67 m a.s.l.: its mean annual temperature is -6.4 °C (January mean -20 °C, July +14 °C) and average precipitation is ~330 mm.y^{-1}, 40 % falling as snow.

In the eastern extremities a glacial spillway divides the largest dolomite plateau into "Mahony Dome" and "Tunago Dome". The former (~800 km^2) has a central alvar draining peripherally into lakes with overflow sinkholes, turloughs, dessicated turloughs, and stream sinks, all developed post-glacially in regular karst hydrologic sequences. Tunago Dome is similar in extent but was reduced to scablands by a sub-glacial mega-flood from the Great Bear basin; it is a mixture of remnant mesas with epikarst, and wetlands with turloughs in flood scours. Both domes are largely holokarstic, draining chiefly to springs at 160–180 m a.s.l. in the spillway.

The eastern limit of overthrusting is marked by narrow ridges created by late-glacial hydration of anhydrite at shallow depth in interbedded dolostones and sulphate rocks. Individual ridges are up to 60 km long, 500–1,000 m wide, 50–250 m in height. They impound Lac Belot (300 km^2), Tunago Lake (120 km^2) and many lesser lakes, all of which are drained underground through them. In the main overthrust structures, the Norman Range (Franklin Mountains) is oriented parallel with the direction of Laurentide ice flow. It displays strongly scoured morphology with elongate sinkholes on its carbonate benches. In contrast, the Bear Rock Range is oriented across the ice flow, has multiple cuestas, is deeply furrowed and holokarstic but preserves pinnacle karst on higher ground due to karst-induced polar thermal (frozen-down) conditions at the glacier base there.

LITTLE LIMESTONE LAKE: A BEAUTIFUL MARL LAKE IN MANITOBA, CANADA

Derek Ford
School of Geography and Earth Sciences, McMaster University, Canada, dford@mcmaster.ca

Marl lakes are those accumulating fine-grained bottom sediments that include at least 15 % $CaCO_3$. They are found worldwide. The most visually attractive, however, have higher proportions of $CaCO_3$, with crystallites precipitating in the water to give it a rich and opaque duck-egg blue colouration. From the literature, such lakes are largely limited to recently glaciated carbonate rock terrains. Most are also shallow, with much or all of the water column being in the photic zone.

Little Limestone Lake, (Lat. 53°47’N, Long. 99°19’W in the province of Manitoba) is the finest example that the author has seen. It stands out sharply from neighbouring lakes in summertime colour satellite imagery due to the intensity and uniformity of its colour. The lake occupies a shallow glacial trough scoured in a plain of flat-lying cyclothem dolomites. It is ~12 km long, 1–5 km wide, rarely >7 m deep. Including bordering wetlands, it occupies ~45 % of the area of an elongated, narrow topographic basin. Recharge is through impoverished boreal forest with little soil cover; it discharges chiefly as springs and seeps along and below the shore. Mean annual temperature is ~0 °C, and precipitation is ~475 $mm.y^{1}$.

Previous studies of springs in the surrounding region showed ground waters to be simple bicarbonate composition, with TDS = 230–300 $mg.l^{-1}$ (Ca 40–60 $mg.l^{-1}$, Mg 30–40 $mg.l^{-1}$). Grab sampling at 27 sites throughout the lake found the waters de-gassed to 125–135 $mg.l^{-1}$, placing them in the mid-range of one hundred marl lakes investigated in more detail in the British Isles. Ca was reduced to 25–30 $mg.l^{-1}$, while Mg was stable at 30–40 $mg.l^{-1}$. There were 2–3 $mg.l^{-1}$ of free CO_3 in two fully analysed samples, indicating that plankton photosynthesis might be occurring. However, samples of the bottom marl were predominantly inorganic in their composition.

Little Limestone Lake is visually spectacular because it is almost entirely groundwater-fed, with a ratio of recharge area to lake area that is low. It has no large, chemically equilibrated, surface streams entering it. In contrast, the dozens of nearby lakes (similar, larger or smaller in size) are regularly flushed by channelled storm water and, although they also produce some carbonate marl, cannot maintain high densities of crystallites in suspension. Little Limestone Lake was placed under legislated protection as a provincial park in June 2011.

1. Marl lakes

Sediments accumulating on lake floors may be divided into: (1) *clastics*, which are fragments of insoluble rocks carried into the lakes by rivers or the wind; (2) *organics,* consisting of animal or vegetal material carried in by air or water currents from surrounding land, and the remains of fish, molluscs, plankton, etc. created in the water body itself; (3) *precipitates and evaporites,* crystalline or micro-crystalline minerals created by organic or inorganic chemical processes along the lake shore, on the bottom, or in the water column and mechanically settled out of it. At the global scale, mixtures of clastic and organic sediments in varying proportions are overwhelmingly predominant in the world’s lakes. Amongst the chemical class evaporite lakes and ponds are more numerous than precipitate lakes (including marl lakes), and probably quantitatively predominant in bulk terms because much greater tonnages are being deposited in them each year. Lakes in which carbonate precipitates make up a significant proportion of the sediment accumulating on the floors are thus comparatively rare. In a popular sedimentological classification of them mixtures of 25–75 % calcium carbonate with clay or silt or non-carbonate organic debris are considered to be “marl” (Schurrenberger et al. 2003). They have the feel and appearance of soft mud or ooze. Some authorities would extend “marl” to include sediments with up to 95 % calcium carbonate provided that they remain soft, i.e. unconsolidated. An essential feature of the most attractive marl lakes everywhere is that there are also calcium carbonate micro-crystals (“crystallites”) in suspension in sufficient concentration in the water column to scatter sunlight and create strong and opaque blue colouration.

Lakes where marl contributes between 5 % and 95 % of the bottom sediments (marl lakes *sensu lato)* are found in every region of the world where there are large quantities of limestone and/or dolomite to contribute the essential calcium ions, and the climate is humid enough to maintain the lakes and keep the concentrations of dissolved solids in them well below the levels where evaporite deposition begins. Most climatically humid regions and the wetter fringes of the sub-humid/semi-arid regions qualify. However, it is recognised that a disproportionately large number of marl lakes are to be found in the glaciated regions, including perhaps a majority of the visually very attractive. Most marl lakes that have been described in the scientific literature are located in the glaciated regions of northern Europe and North America.

Following Pentecost (2005, 2009) there are two different paths to the creation and deposition of the marl, *biogenic* and *abiogenic* (inorganic). Processes in a given lake may be completely dominated by one of them, or be a mixture of both that may differ in its proportions as the seasons progress. The abiogenic is the simple process of limestone or dolomite inorganic dissolution, with crystallite precipitation following when CO_2 degasses from the Ca, Mg, HCO_3 solution due to warming or loss of pressure or both.

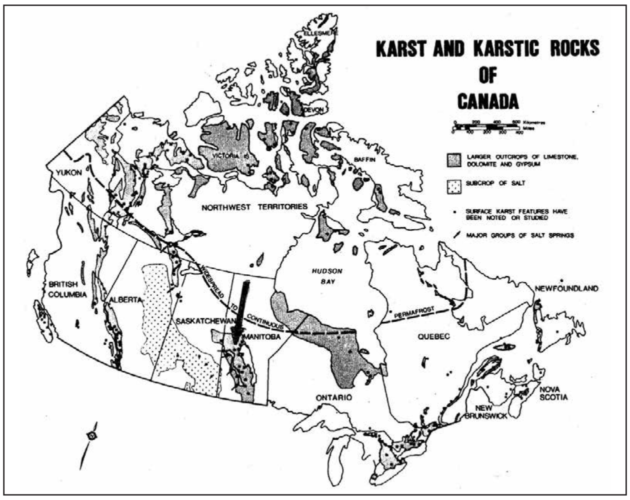

Figure 1. Location of Little Limestone Lake, Manitoba.

Wholly biogenic deposits may arise because photosynthesis in fresh waters creates many species of microscopic algae and bacteria. Pentecost (2009) focuses on the common green alga *Chara* but there are a host of alternatives. In the first step: $2HCO_3^- \rightarrow CH_2O_{\text{(photosynthesis)}} + O_2 + CO_3^{2-}$. There is abundant HCO_3^- in karst lake waters, e.g., McConnaughey et al. (1994) found that macrophytes, chiefly *Chara*, extracted ~23 grams C/m^2 during the growth season in a Minnesota marl lake. With abundant Ca^{2+} also being present via the inorganic path, step 2 proceeds: $Ca^{2+} + CO_3^{2-} \rightarrow CaCO_{3\text{ (calcite)}}$. "calcite begins to form in strongly alkaline surface regions of the internodal *Chara* cells and subsequently envelops almost the entire plant. During the later stages of calcification additional inorganic precipitation may be taking place but this has been little studied" (Pentecost 2009). The inorganic calcite probably accretes to the outer surface of the alga in the manner that it accretes to larger plants to form *tufa* deposits in many streams and lakes around the world. The algae remain very tiny, however, suspended in the water and scattering incident light, settling slowly downwards only if conditions become very calm.

2. Little Limestone Lake and its setting

Little Limestone Lake (Figs. 1, 2; Lat. 53°47'N, Long. 99° 19'W in the province of Manitoba, Canada) is the finest example of a marl lake that the author has seen in many years spent in glaciated karst regions. It stands out sharply from the neighbouring lakes in summertime colour satellite imagery due to the intensity and uniformity of its duck-egg blue colour. Viewed from the shore or in a boat it is equally colourful. For these reasons the Manitoba chapter of the Canadian Parks and Wilderness Society, a national conservation body, argued for its protection for many years. The Conservation Branch of the provincial government requested an independent evaluation by a specialist (Ford 2010), which resulted in a park protection area being proclaimed in 2011.

Little Limestone Lake is one amongst hundreds of small lakes in the Interior Lowlands geologic region of North America. It is located a few kms northwest of the much larger Lake Winnipeg, and drains to Hudson Bay (Fig. 1). The bedrocks are platformal dolomites of Silurian age totalling approximately 80 m in thickness that dip very gently westwards (Bezys 1991; Bezys and Kobylecki 2003). Local relief upon them is never more than 70 m, created chiefly by glacial scour, or the deposition of glacial moraines during the recession of the last Laurentide Continental Icesheet ~11,000 years ago. A sample bedrock section exposed in a road cut a few km south of the lake is shown in Figure 3. The strata are a cyclic succession of regular beds varying from "medium" (10 cm) to "massive" (>100 cm) in thickness. The thicker beds are mechanically stronger and so survived glacier scour more readily. Clint-and-grike solutional pavement (epikarst) has developed on them in post-glacial times (Ford 1987; Ford and Williams 2007). They also have a high density of vugs, which can increase the matrix permeability of the rock and thus the quantities of dolomite taken into solution by groundwater permeating through it. Examples of the cliffs on massive dolomites and epikarst on thinner beds along the shores of Little Limestone Lake are shown in Figures 4 and 5.

In Figure 2 the boundaries of the Lake basin are drawn conventionally to follow the surface topographic divide because no karstic diversions of groundwater flow are known. The basin is ~20 km in length, 5–8 km wide. It has an area of ~91 km^2, of which 36 km^2 is occupied by the Lake itself. Pond A (~2 km^2; Fig. 2) is a former arm of the lake that is now separated by wetlands but still drains into it; it has negligible ground water supplies of its own and its water is clear, not opaque and blue. The dry land area that is believed to contribute to the lake is thus ~53 km^2. Wetlands at or very close to the lake level occupy ~3.5 km^2 of this and the balance consists of gentle side slopes and broad plateaus. The lake is at ~267 m above sea level and the highest ground is around 290 m a.s.l.

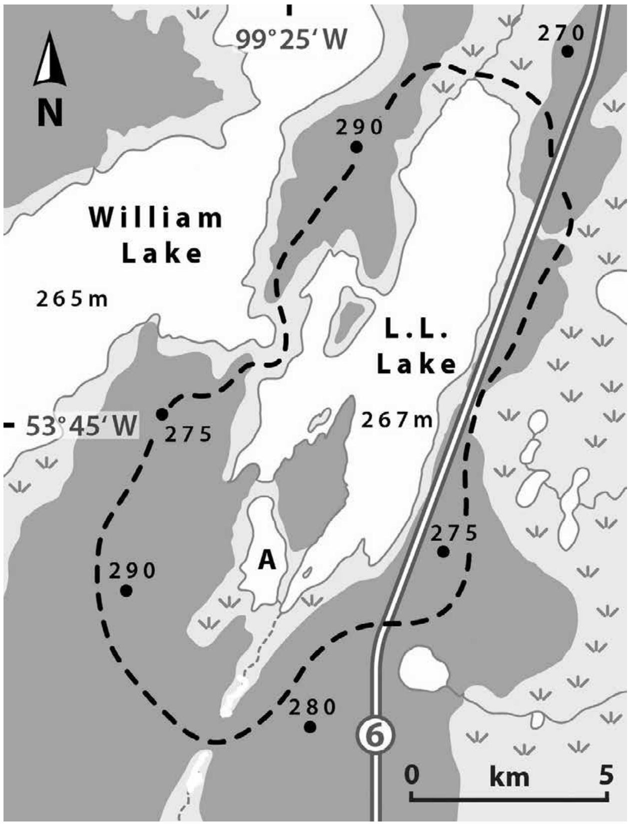

Figure 2. Sketch map of Little Limestone Lake. The watershed is shown by dashed line.

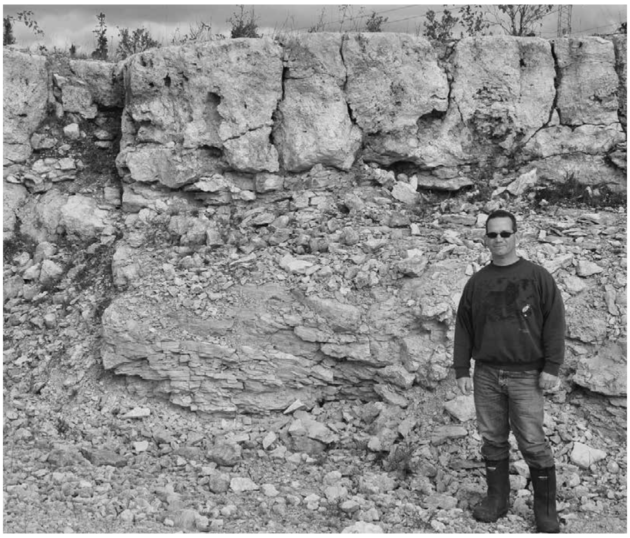

Figure 3. A typical section of the cyclic dolomite beds at Little Limestone Lake.

There is no bathymetric map of Little Limestone Lake and the bottom is always obscured by the suspended load in summer. The geologic and physiographic setting indicates that the lake is likely to be shallow everywhere. A few measured depths suggest that much of it has a flat floor at 7.0 to 7.5 m. This is comparatively deep for a marl lake but not as great as the deepest mentioned in Pentecost's 2009 sample of 100 such lakes in the British Isles. At 7.5 m the waters are fully in the photic zone. Sample cream-coloured carbonate oozes were dredged from the bottom there.

At its north end Little Limestone Lake is drained by a regular stream channel that passes through a wetland into a lake about one metre lower (266 m a.s.l.). A small spring-fed stream flows into the southern end. To the west William Lake, a much larger water body, is at 265 m a.s.l. To the east and south there are extensive wetlands and smaller dolomite plateaus draining 18–20 km eastwards into Lake Winnipeg at 217 m a.s.l. The important consequence is that the Little Limestone Lake basin, although it functions as a water-retaining shallow trough, can be envisioned as an elongated hydrological ridge or "high" perched between drainage to lower lake levels around it. The Lake plus Pond A and associated wetlands occupy nearly 46 % of the basin, a very large proportion. Recharge from the remaining ~54 % is almost entirely by groundwater that has passed through the dolomite. The basin is not prone to flushing by mud-laden flood waters from proportionally greater recharge areas, as the majority of other lakes in the region are. Under the natural conditions that have prevailed for at least some thousands of years here a delicate physical, chemical and (probably) biogenic balance has been able to build up and establish the remarkable marl blue colouration. The current climatic conditions are Cool Continental (Koppen type D). The mean annual temperature is ~1.0 °C and precipitation is 475 mm.y^{-1}. The natural vegetation is Boreal Forest (coniferous).

Nearly flat plateau and bench surfaces in bedrock are predominant in the recharge areas. There is thin and discontinuous glacial till cover on them due to erosion by over-wash immediately after the ice receded. There is a nearly 100 % cover of mosses, lichens, flowers, juniper and other low shrubs, and forest litter. The trees are widely spaced, slow-growing or stunted in many places, reflecting the edaphic drought that occurs where the dolomite surfaces are efficiently drained by epikarst (Figure 6). Forest fires have broken up the karst on thinner beds, increasing the efficiency of groundwater recharge. The greatest straight-line distance that groundwater must flow from these uplands to the lake is no more than 3–4 kms, giving hydraulic gradients (depth/length gradients) of 5 m.km^{-1} or more. There are some seepages in the cliffs and at the water line in the lake but most ground water discharge is below that, perhaps because industrious beavers have raised the lake level by ~0.5 m in recent decades.

Figure 4. Cliffed shore with groundwater outlets at and below the waterline.

3. Water chemistry

The water chemical characteristics of the Lake itself have not been studied in detail. However, McRitchie (1994, 1995) carried out systematic sampling at springs and seeps in the dolomite escarpment immediately south of it, plus two water samples from springs on William Lake. Seventy water samples were analysed for the standard water quality variables plus trace concentrations of economic minerals and of contaminants. All of the waters were simple calcium bicarbonate ground waters typical of clean dolomite terrains. Total hardness ranged between 230 and 300 mg.l^{-1}; Ca 40–60 mg.l^{-1}, Mg 30–40. The waters were saturated or supersaturated with respect to calcium carbonate under standard atmospheric conditions. Na, K, SO_4 and Cl were negligible in amount. At each site there was one-time sampling only and in most cases the water was taken from the spring itself before it had had any opportunity to de-gas its CO_2 content or make other adjustments to open air conditions.

McRitchie (1994) described what happened downstream, however – precipitates quickly appeared, as sand-sized particles at first but rapidly shrinking in size downstream and ceasing to form after 200–300 m of flow in the open channels. In the ponds at some springs there were organic-rich mats of material. Downstream there was only cream-grey carbonate ooze, very like that collected from the bottom of Little Limestone Lake. The oozes were almost entirely $CaCO_3$, chiefly of inorganic origin although one of four samples may have contained as much as 10 % organics (i.e. from photosynthesis, as described above).

Figure 5. Shoreline recharge directly from the epikarst.

In September 2010 the author took one near-shore bulk water sample from the surface of Little Limestone Lake and a second from -2.0 m in the centre. Comprehensive standard analyses (ALS Laboratory,Winnipeg) found the two samples nearly identical, indicating that at least the upper two metres of the lake are uniform in composition. Na, K, Cl and SO_4 were negligible in amount. Total hardness (as $CaCO_3$) was 200 mg.l^{-1}. This is significantly less than the values between 230 and 300 mg.l^{-1} that Ritchie obtained at the springs and seeps from the dolomites. It suggests that the Lake waters have de-gassed CO_2 and precipitated large amounts of their dissolved load. This explanation is substantiated by the Ca: Mg ratios of 26: 33–34. In the large majority of published dolomite karst water compositions the ratio is the reverse of this (60: 40 to 70: 30 in favour of Ca^{2+} until vigorous precipitation begins). The detection of 2–3 mg.l^{-1} of CO_3^{2-} also indicates de-gassing, at a pH above 8.3.

Determination of free CO_3 in the lake waters is a hint that photosynthesis was occurring.

Water temperature and electrical conductivity were measured at a depth of ~1.0 m at 27 different points in the Lake. The Krawczyk and Ford (2006) "best fit" equation for "clean" bicarbonate waters (salts + sulphates + nitrates + phosphates <10 %; electrical conductivity <600 µS) was used to calculate total hardness as mg.l^{-1} $CaCO_3$:-

$$TH = 0.53\ EC - 1.6\ (R^2 = 0.93;\ n = 2300) \quad (1)$$

The principal finding was the uniformity of shallow water chemistry everywhere on the Lake proper. Despite a range of temperatures from 12.8 to 17.4 °C during the two days of sampling, EC was in the narrow range of 240–250 µS with one exception. From Equation 1, estimated $CaCO_3$ concentrations of 126–132 mg.l^{-1} place the Lake waters comfortably in the mid-range that Pentecost (2009) has cited in his sample of more than one hundred marl lakes and ponds in the British Isles.

The one exception was the small spring-fed stream draining the southern epikarst. It entered the Lake at a temperature of 11 °C, EC = 296 µS, and was clear (no blue opacity). Twenty metres further out into the Lake sampling a few minutes later yielded T = 14.4 °C, EC = 247 µS. This suggested rapid warming with net precipitation of ~25 mg.l^{-1} $CaCO_3$.

Figure 6. Recently burned forest on medium-bedded dolomite. The epikarst surface has been broken up by the heat, by toppling and by frost.

Concerning the stability of the density and hue of the colour, my previous visits to the Lake (1984, 2004) were of short duration during warm sunny afternoons which led me to wonder whether there might be a daily "blooming" of crystallites in response to solar warming, such as occurs in knee-deep water on the Bahamas Banks for example. It is now appreciated that this is not the case; the crystallites can have a duration of at least many weeks in suspension during the ice-free period on the Lake, giving sufficient time for winds to mix them thoroughly across the surface. Further, many authorities contend that lakes that are as shallow as typical marl lakes do not develop strong thermal or other stratification (Pentecost 2009); the physical and chemical conditions are broadly similar from surface to the bottom. From the physical chemistry some increase in the rate of precipitation is to be expected at the warmest times of the day: at Little Limestone Lake other observers have reported their qualitative impressions that there is some increase in density (opacity) then.

4. Conclusions and recommendations

Little Limestone Lake has outstanding blue ("marl lake-type") colouration because its elongated, small and shallow, basin is delicately perched between much larger basins draining to east and west respectively and thus is protected from flushing or clastic or organic detrital input by large surface streams during any strong thaw or rain flood events. The ratio of recharge area to lake area is low. Almost all annual recharge is from the combination of seasonal snowmelt and perennial groundwater flow directed through the enclosing dolomites. From current knowledge it appears that the water chemical behaviour that determines the striking blue colouration of the Lake during the summer is quite robust. The bulk of $CaCO_3$ crystallite precipitation appears to be of physical origin but the contribution of photosynthesis is not adequately understood at present.

The location is remote and the local population is very small. However, there are nickel exploration prospects in Canadian Shield rocks beneath the dolomites around William Lake that touch the western side of Little Limestone Lake. Physical threats to the lake could arise if the volumes of water flowing into it were substantially increased or diminished by any exploration or other development. Both could impact the colouration and its chemical stability in ways that are difficult to forecast. Chemical hazards could include acidification or introduction of other contaminants that kill off the pertinent biota if biogenic activity is a crucial contributor to the carbonate precipitation. Heavy gasoline-powered boat traffic could also pose a threat. It is hoped that the creation of the provincial park will deal with these problems.

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