TERRAIN GEOCHEMISTRY SURVEYS, PERMAFROST STUDIES, AND ARCTIC LIMNOLOGY, DISTRICT OF KEEWATIN, N.W.T.: IMPLICATIONS FOR WATER QUALITY MONITORING IN THE NORTH

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ABSTRACT

Geochemical studies and surveys conducted by the Geological Survey of Canada have provided considerable information about the natural geochemical variations in glacial drift, lake sediments, and lake waters in south-central District of Keewatin. In addition to their intended contribution to mineral exploration, these activities yielded much basic background data that may be applied to the planning of water quality monitoring programs in the region.

Studies of permafrost features, and arctic limnology have furnished knowledge about natural geomorphic and diagenetic processes that influence surface water quality. Cryoturbation, on land and in the shallow areas of lakes underlain by permafrost, plays a major role in the transfer of particulate and dissolved drift constituents to surface waters. In spite of the abundance of mineral detritus on shore, profundal lake sediments are typically highly diatomaceous and possess conspicuous oxic surface layers that likely have a strong capacity to sequester both nutrients and trace metals.

INTRODUCTION

During the late 1960's and 1970's various studies having significance to current concerns about water quality in the North were conducted in the District of Keewatin by the Geological Survey of Canada. These efforts ranged in scale from regional geochemical surveys of overburden, lake sediments, and surface waters for mineral inventory purposes to more detailed terrain studies to investigate the use of glacial till as a sampling medium for mineral exploration. In the course of this work particular attention was paid to permafrost features, such as rib-and-trough structures and mudboils, which play important roles in the transfer of soluble and insoluble components of the drift to surface waters. Investigations intended more specifically to obtain environmental information included examination of present lacustrine sedimentary and diagenetic regimes and past lake history along the corridor of the then-proposed Eastern Arctic Gas pipeline. Although far from providing an exhaustive data base for environmental monitoring, these studies have yielded much basic information about terrain geochemistry and some of the cryogenic and limnologic processes that should be considered when formulating strategies for assessing possible future changes in water quality in the region.

The present article outlines the types of studies that were carried out in south-central Keewatin by the Geological Survey of Canada and the nature of the data that was collected. The information has been disseminated in various previous articles, reports, and theses, many of which are available through either the publications office or the library of the Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, K1A 0E8.

STUDY AREA

Studies were conducted primarily in south-central District of Keewatin in the area known traditionally as the Barrens (see inset Index Map, Fig. 1). The region is characterized by its subdued relief and poorly integrated drainage, and the existence of continuous permafrost to considerable depths. The barren aspect of this landscape derives mainly from the effects of the rigorous, subarctic climate, which limits arborescent vegetation to ground-hugging dwarf birch and willow. In spite of the dry atmospheric conditions, the tundra is richly supplied with surface water in innumerable ponds and lakes. During the summer ice-free season (roughly July through September for most lakes usable by float-equipped aircraft) thawing of the active layer on shore occurs to depths of up to a metre or more, depending on the nature of the substrate and the thickness of the insulating vegetation mat. Baker Lake, the largest permanent settlement in the Barrens, has a mean annual air temperature of about -12 °C and receives about 20 cm of precipitation annually, mostly as rain between May and October (Thompson 1967).

District of Keewatin is underlain principally by Precambrian rocks of the Churchill Province of the Canadian Shield. Much of the bedrock is crystalline, of igneous and metamorphic origin with predominantly granitic composition. Notable exceptions include outcrops of the Dubawnt Group (an unmetamorphosed Proterozoic sedimentary and volcanic red-bed sequence) and the Rankin Inlet-Ennadai Greenstone Belt, which includes volcanic and sedimentary units (Fig. 1). During the last glaciation southern Keewatin was bisected by a major dispersal centre for the Keewatin sector of the Laurentide Ice Sheet. The radial pattern of erosion, transportation, and redeposition of bedrock components by ice flowing from this centre played a dominant role in the genesis of modern landforms. As a result of isostatic depression, a considerable part of southern Keewatin was inundated by marine waters of the Tyrrell Sea (the precursor to modern Hudson Bay) during deglaciation (Fig. 2), leading to reworking of upland surficial deposits and
Figure 1
Generalized bedrock geology, southern District of Keewatin, N.W.T.

Figure 2
Generalized surficial geology, southern District of Keewatin, N.W.T.
accumulation of winnowed fine material in low-lying areas, many of which are occupied now by lakes. Cryogenic processes have probably been the major agent of postglacial (and post-marine) landform modification in the region.

TERRAIN GEOCHEMISTRY SURVEYS

Extensive sampling of overburden and lake sediments and waters in Keewatin was undertaken by the Geological Survey of Canada in order to assess more effectively the potential for economic mineralization in the region and to provide reconnaissance-scale targets for follow-up investigations. Studies of surficial geology were conducted concurrently, to evaluate the extent to which glaciation has modified the geochemical signature of the land surface through comminution and dispersal of rock constituents.

Overburden Sampling

The most promising results from the overburden sampling program were achieved using the clay-size fraction (<2 μm) from glacial till, which forms most of the surficial sediment cover in Keewatin. Samples were obtained from shallow pits dug by hand in the centres of mudboils, which are characteristic permafrost features that naturally cycle weathered and unweathered till through the active (seasonally thawed) layer (see later discussions). Because of its texture, till in this part of Keewatin has a propensity to form mudboils (Shilts 1978). The relatively unweathered till in mudboils represents the least-reworked secondary derivative of the original source rocks; hence, given sufficiently precise information about glacial dispersal patterns, the geochemical signature of the till can be highly diagnostic of the bedrock geology up-ice of the sample site. The relation between bedrock geochemistry and glacial sediments has been demonstrated at both regional and local scales from such studies in Keewatin (Fig. 3). (Renz and Shilts, 1980; Riiber and Shilts, 1974; Shilts, 1972, 1977, 1980, 1984).

Figure 3

Example of regional dispersal of Zn southeastward from Zn-rich rocks lying north of Baker Lake in the <2μ fraction of till.

Lake Sediment and Water Sampling

Lake sediments and water were sampled over selected areas from centre-lake sites using float-equipped helicopters. Sediments and waters provide integrated samples of the secondary dispersion of geochemical signals from the various materials in lake catchments, including both bedrock and overburden. Because the geochemical signature of glacial drift is displaced from the bedrock source (and may be altered subsequently by weathering processes and reworking), anomalies detected from sediment and water sampling may not be conclusive indicators of bedrock composition. Conversely, such integrated samples of locally-derived particulate and dissolved material may yield more directly usable information with respect to local water quality than data from a single source material on shore. Studies in the Kaminak Lake area (Hornbrook and Jonasson 1971) provide a conspicuous example of distinct hydrogeochemical anomalies related to both bedrock and overburden sources within the same survey area. The lakewater sampling clearly delineated the presence of a glacial dispersal train rich in Cu, Ni, and Zn overlying barren bedrock, while also identifying a prominent Hg anomaly in a neighbouring area attributable to local Hg-rich bedrock. Both features have significant implications for monitoring anthropogenic heavy metal contaminations in Keewatin, since they highlight the possible existence of unrecognized, naturally-occurring "contamination".
Although such terrain geochemistry surveys have provided only patchy coverage in Keewatin, the resulting body of data nevertheless represents a valuable store of information about natural geochemical variations in surface waters and contributing sources of dissolved and particulate material on shore. Table 1 summarizes survey data that are available for south-central District of Keewatin. Descriptions of sampling and analytical methods are included in many reports. Detailed discussions of the geochemical techniques used by the Geological Survey of Canada are also presented by Jonasson et al. (1973).

Table 1

<table>
<thead>
<tr>
<th>Sample Medium</th>
<th>Area</th>
<th>Parameters</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>lake sediment</td>
<td>NTS 65A, 65B, 65C</td>
<td>Cu, Ni, Pb, U, Zn</td>
<td>Hornbrook 1977 a-e</td>
</tr>
<tr>
<td></td>
<td>55M, 65P</td>
<td>(plus others)</td>
<td></td>
</tr>
<tr>
<td>lake water</td>
<td>Kaminak Lake area</td>
<td>Cu, Hg, Ni, Zn</td>
<td>Hornbrook and Jonasson 1971</td>
</tr>
<tr>
<td>(NTS 55L)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>glacial till and</td>
<td>Kaminak Lake area</td>
<td>Cu, Ni, Pb, Zn</td>
<td>Shilts 1973</td>
</tr>
<tr>
<td>esker sediment</td>
<td>and Southern Lake areas</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(NTS 55L)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>glacial till</td>
<td>Kaminak Lake area</td>
<td>Cu, Zn</td>
<td>Ridler and Shilts 1974</td>
</tr>
<tr>
<td>(various fractions)</td>
<td>(NTS 55L)</td>
<td>(plus others)</td>
<td></td>
</tr>
<tr>
<td>glacial till (&lt; 2μ fraction)</td>
<td>Heninga-Kaminak-</td>
<td>Cu, Ni, Zn</td>
<td>Shilts 1974</td>
</tr>
<tr>
<td></td>
<td>Quartzite Lake area</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(NTS 55L, 65H)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boothia Peninsula</td>
<td>U</td>
<td>Shilts and Klassen 1976</td>
<td></td>
</tr>
<tr>
<td>(NTS 57A-D,F,G)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Kaminak Lake area      | U                           | Klassen and Shilts 1976a-
| (NTS 55L, 65H)         |                             | b                  |                            |
| Baker Lake area        | U                           | Klassen and Shilts 1977b |
| (NTS 55M,65D,65P,66A)  |                             |                  |                            |
| Cadli area             | Cu, Ni                      | Dilabio and Shilts 1977 |
| (NTS 65H)              |                             |                  |                            |
| Rankin Inlet area      | Co, Cr, Cu, Ni              | Dilabio and Shilts 1977 |
| (NTS 55I, 66)          |                             |                  |                            |

Note: This table contains a representative selection of reported surveys, but does not include a wider range of elements analysed but not published. Archived samples from these projects will be re-analysed for more elements in the next few years in conjunction with a Federal/Provincial mineral exploration research program.

PERMAFROST STUDIES

Mudboils

Studies of permafrost features in District of Keewatin were carried out as a result of the need to understand the nature of cryogenic modification of overburden materials sampled for regional geochemical surveys. Mudboils represent a common and easily identifiable indicator of perennially frozen till or other similar poorly sorted sediment containing silt or clay. They typically consist of round to elongate patches of bare soil 1 to 3 m in diameter, commonly surrounded by a raised rim of vegetation (Fig. 4a). Depending on the local edaphic and climatic conditions (which may limit plant growth) and the frequency of tundra fires, the vegetation rims may be reduced or absent (Fig. 4b). In the latter case the mudboil may be encircled by a shallow trough containing frost-heaved cobbles and pebbles.

Figure 4a: Close-up view of a mudboil showing freshly extruded till in the centre (darker sediment under tape measure) surrounded by older, weathered material (lighter coloured sediment). (GSC #203010-J)
Mudboil formation in Keewatin tills is promoted by natural moisture content near or at the relatively low liquid limit of typical till when it is thawed in the active layer. Even a slight increase in moisture content, induced by internally or externally generated stresses (such as cryostatic pressure or loading), can lead to rapid liquefaction of the till. Excavation of mudboils has shown them to be the surface expressions of diapiric structures (Fig. 5). Changes in hydrostatic pressure resulting from annual freezing and thawing, rainfall, differential loading caused by contrasting specific gravities of surface sediments, or loading by animals or man can cause diapiric extrusion of liquefied till that originates near the base of the active layer. Subsequent winnowing of clay-sized material by surface runoff and weathering eventually lead to build-up of a somewhat rigid sandy carapace onto which till is periodically extruded.

The presence and frequency of mudboils as well as their degree of activity influence the quality of surface waters in Keewatin, since these features represent an important mechanism for mobilization and downslope transport of particulate and dissolved material from the perennially frozen terrain. Transportation of soluble constituents to local surface waters probably occurs readily in runoff from snow melt and summer rains. Detrital matter, on the other hand, may be intercepted temporarily by vegetation, especially in mudboil rims. Such stored sediment becomes available to local surface waters very rapidly following tundra fires, which often completely consume the mass of living and dead plant matter in mudboil rims and on other vegetated surfaces (Wein and Shilts 1976). In addition to mineral detritus, the pulse of ash washed into local water bodies after a fire probably contributes a substantial flux of nutrients to the receiving waters.
In addition to scouring patterned littoral areas, drifting lake-ice during spring break-up commonly causes extensive shoreward transport of nearshore sediments, leading to buildup of ice-push ridges on windward shores. Drifting ice may also disrupt shoreline vegetation, as well as redistributing sediments from shallow areas into deeper sites by rafting.

Sublacustrine Holes

Sublacustrine holes represent an additional type of subaqueous feature that commonly occurs in shallow areas of lakes underlain by permafrost in Keewatin (Shilts and Dean 1975). Although probably not genetically related to the presence of permafrost, these features are significant to the present discussions because they indicate that energetic reworking of fine sediments can occur following deposition in a lake. Sublacustrine holes are round depressions, typically 0.5 to 4.0 m in diameter, lying in water depths of up to about 2.5 m, that are excavated into easily eroded silty sediments (Fig. 9). Most likely the holes result from forceful downward flow of meltwater through holes in the ice as bottom-fast ice detaches and rises abruptly during spring break-up. Such features have been observed in arctic marine settings where they are called "strudel". (Reimnitz et al. 1974). Because organic detritus tends to grow and accumulate preferentially in these sublacustrine holes, the sediments in areas where holes are abundant may be anomalously rich in organic matter compared to typical lake-centre sediments.

Environmental studies conducted by the Geological Survey of Canada in anticipation of construction activity along the proposed Polargas pipeline route included limnological investigations in various lakes in south-central Keewatin. The most detailed studies were undertaken in the so-called 'Whatever' Lake watershed (near Ferguson Lake), in which divers made extensive observations of submerged features and obtained numerous grab-samples and cores of lake-bottom materials (Edwards 1980). A considerable amount of limnological information was also obtained from studies in the Kaminak Lake area (Klassen 1975; Shilts et al. 1976). These efforts yielded information about sediment composition and diagenesis, and the postglacial history of lakes in the Barrens (see also Edwards 1978).

Many of the studies were conducted in relatively deep lakes (having a significant area in excess of 10 m depth), which are particularly important habitats for local fish populations. Such lakes apparently remain well-oxygenated throughout the year, judging by measurements made during the summer months (when the water column commonly remained saturated with respect to oxygen), and the extenscive development of oxic
sediment surface layers observed by divers, and in dredge and gravity core samples. Thermal stratification occurs briefly during the summer months in many lakes, although wind-generated mixing may induce overturn at any time. Measurements of water quality parameters from a suite of lakes in south-central Keewatin yielded the ranges of values listed in Table 2.

Table 2: Ranges for water quality parameters measured in 22 lakes in the Baker - Ferguson - Kaminak Lakes area. (Data mostly from Shilts et al., 1976, Table 51.1, and unpublished field data collected July and August 1977.)

<table>
<thead>
<tr>
<th></th>
<th>Temperature °C</th>
<th>pH</th>
<th>Dissolved Oxygen ppm</th>
<th>Conductivity umhos/cm</th>
<th>Redox Potential mv</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep Lakes</td>
<td>10-13.3</td>
<td>5.9-6.7</td>
<td>10.6-14.4</td>
<td>13-30</td>
<td>285-335</td>
</tr>
<tr>
<td>(much of the lake &gt; 10 m deep)</td>
<td>(surface)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shallow Lakes</td>
<td>12.5-15.0</td>
<td>6.3-7.3</td>
<td>11.7-12.8</td>
<td>15-40</td>
<td>130-300</td>
</tr>
<tr>
<td>(mainly &lt; 10m deep)</td>
<td></td>
<td></td>
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</tbody>
</table>

Lake Sediments

Comparatively little postglacial or postmarine sediment has accumulated in deep lakes during the 4000 to 6000 years since deglaciation and marine emergence in central Keewatin. ‘Modern’ lacustrine sediment in offshore sites (‘lake gel’) is rarely as much as one metre thick, overlying bedrock, till, or previously deposited glaciolacustrine or glaciomarine sediments. Lake gel is characterized by its gelatinous texture, high water content (> 80% by weight), low organic matter content (< 10% by weight), and the existence of well-defined diagenetic zonation, which is delineated by the conspicuous presence of abundant authigenic mineral precipitates. Microscopic analyses of core-top sediments have revealed that the most plentiful primary sediment constituent consists of siliceous tests of diatoms, as free filaments and frustules, and incorporated within fecal pellets excreted by microcrustacean zooplankton and benthic grazers (Fig. 10). Mineral detritus, which typically increases in abundance progressively with depth in the sediment column from often-negligible amounts near the surface, comprises mainly silt-size quartz with lesser, variable amounts of feldspar, mica, and mafic minerals.

The most distinctive feature of the diatomaceous lake gel is the extensive development of an oxidized surface layer, which is in sharp contrast to the meagre oxic zone development that occurs in highly reducing, organic-rich gyttja of lakes in more temperate regions. The upper 5 to 30 cm of the sediment column is generally stained the characteristic reddish-orange colour of oxidized iron phases and contains abundant orange and black, sand-size micronodules of iron and manganese oxyhydroxides. The base of the oxic zone may be marked by a band of concentrated oxide particles, or more frequently by a continuous, 0.5 to 1.0 cm-thick oxide crust consisting of a distinct thin upper layer of black, Mn-rich oxide overlain by a thicker layer of bright orange, Fe-rich material. The underlying sediments are typically olive-grey in colour overall, punctuated by numerous horizontal black laminae. Upon exposure to the air, the reduced sediments readily oxidize to a pale brown colour, indicating the presence of free ferrous ion (Fe²⁺), and the black laminae gradually alter to the bright blue colour that characterizes the presence of vivianite (Fe₃(PO₄)₂·8H₂O). The upper few centimetres of the reduced sediments occasionally contain co-existing residual iron oxide and newly formed vivianite. This strong diagenetic zonation is illustrated diagrammatically in Fig. 11.
The diagrammatic reactions that are responsible for the striking chemical zonation of the sediments involve mainly oxidation and reduction of iron and manganese phases. These metals enter the lake as dissolved and complexed species of various forms that are ultimately deposited in the surficial sediments. Intense oxidation in the sediment surface layer (fostered by permanently oxidizing lake waters and the small flux of organic matter) promotes formation of coatings and micronodules of iron and manganese oxyhydroxides. Judging by studies of similar deposits elsewhere (e.g. Ingi and Pontor 1986) phosphorus is also concentrated in the surficial layer, largely in association with iron phases, in the form of coprecipitated hydroxyphosphate complexes (see also Nriagu and Dell 1974). Burial of oxidized manganese phases below the flux of organic matter) promotes formation of watings and micronodules of imn and manganese oxyhydroxides. Judging by studies of similar deposits elsewhere (e.g. Ingri and Ponter 1986) phosphorus is also concentrated in the surficial layer, largely in association with iron phases, in the form of coprecipitated hydroxyphosphate complexes (see also Nriagu and Dell 1974). Burial of oxidized manganese phases below the strongly oxidizing surficial layer causes their reduction and the liberated reduced manganese ions migrate back to the base of the oxic zone to form the distinctive upper black layer of the oxidate crust. Reduction of iron oxide phases liberates ferrous and phosphate ions, engendering both formation of vivianite in situ, and recycling of iron back to the oxic zone to form the orange layer of the oxidate crust. Diagenetic activity is also manifested by the accumulation of gas bubbles in the sediments of some lakes, including Yandle Lake (detected during subbottom profile surveys) and Kaminak Lake (observed in cores). Such bubbles probably comprise mostly methane, generated as a result of anaerobic diagenesis of buried organic matters.

In addition to the influence on the behaviour of phosphorus in sediments, the sequence of diagenetic reactions outlined in the previous paragraph should lead to natural partitioning of other elements, such as trace metals, that also tend to coprecipitate with iron and manganese oxyhydroxides. Thus the upper oxic layer (above the oxidate crust) should contain 'contemporary' metal influx, deposited in the sediments during the time taken to accumulate that thickness of sediment, whereas the crust (or equivalent zone of concentrated micronodules) should contain mostly oxide-related metals leached from buried sediment horizons. Trace metals in the underlying reduced sediment would likely occur at considerably depleted levels, shared between resistant primary mineral detritus and secondary phases like vivianite. It should be noted that the regional geochemistry surveys discussed in a previous section sampled only reduced sediments, in order to circumvent the uncertainties introduced by oxide scavenging effects. Indeed, studies of oxic layer sediments have revealed wide variations in trace metal enrichment, even within individual basins, which, if unrecognized, might lead to spurious estimates of local metal loading rates (Klassen 1975; Adshead 1981).

Lake History

Study of the changing diatom floras preserved in sediment cores from the ‘Whatever’ Lake watershed showed that postglacial and (or) postmarine sedimentation in these lakes occurred under two distinctly different limnologic regimes. The early lacustrine phase, represented by the mineral-rich lowermost half or less of the lacustrine sediment section, is characterized by the abundance of alkaliphilous diatoms, particularly species of Fragilaria. These diatoms, which have been recorded elsewhere in newly formed lakes, are indicative of relatively well-buffered waters, such as those to be expected in recently glaciated terrain. A gradual transition to diatoms typical of circumneutral to acidic waters (as exist at present) occurs in concert with declining quantities of mineral detritus and substantial dominance of the sediment volume by diatomaceous material. The transitions from early to late lacustrine phases in the lakes of the studied watershed remain undated; however, it seems likely that these shifts occurred synchronously in response to changes in the local landscape. Various mechanisms could be invoked to explain a decrease in mineralic sedimentation within the last 4000 to 6000 years, including stabilization of the ground surface by vegetation or aggradation of permafrost following the Hypsithermal. The paleolimnological data do indicate that the lakes have been highly unproductive throughout their existence, and that the natural process of gradual acidification is apparently continuing.

DISCUSSION

Terrain geochemistry surveys offer quantitative data that are directly applicable to the problems of planning and assessing water quality monitoring programs. Such surveys provide valuable background data about natural geochemical variations in the environment. They can be applied equally well to the problems of selecting appropriate parameters to monitor and locating representative sample sites. In addition, previously identified geochemical anomalies, such as the mercury contamination in Kaminak Lake, represent obvious targets for more detailed local studies and provide natural case histories for identifying similar features elsewhere. In the Northwest Territories, where anthropogenic effects are presently limited mainly to highly localized impacts from point-source emissions, regional geochemical data of any kind can contribute to baseline environmental assessment.
The permafrost studies and limnological investigations discussed above provide information of a more descriptive nature, the value of which lies primarily in the contribution to our understanding of the natural processes that may influence water quality in Keewatin. Informed assessment of the present state of water quality, and anticipation of future changes (whether related to human activity or not) rests implicitly on the development and refinement of such an understanding. Although these observations are largely qualitative rather than quantitative, several specific issues can be addressed.

Surface waters in much of Keewatin are probably highly susceptible to acidification from acid precipitation owing to the predominance of non-calcareous bedrock and drift, which offer limited acid-neutralizing capacity. The restriction of groundwater activity to the shallow, seasonally-thawed surface layer and the high moisture contents of most overburden materials would also tend to constrain the potential for buffering acidic rainfall and snowmelt. Although potential anthropogenic acidification in the Barrens may be mitigated to some extent by the small total annual precipitation (under present climatic conditions), dry deposition could make the effects as severe as those in more humid areas. Predicting the effects of elevated acid loading is hampered by the limited understanding of the natural capacity for lake sediments to buffer acidity in overlying lakewaters. Little of what is known is likely to be applicable directly to the diatomaceous lake gels encountered in District of Keewatin.

Increased loading of substances such as heavy metals may also be anticipated, through both atmospheric dispersal and local point-source emissions (such as mine-site effluent). Historic changes in loading rates are commonly inferred from the geochemical stratigraphy of recent lake sediment layers. In organic-rich gyttja having limited or non-existent oxide layer development such exercises may provide realistic estimates of changing anthropogenic influence. However, the conspicuous diagenetic effects in the Keewatin lake gels, and in particular the strong evidence for active recycling of buried metal phases, argues against the likelihood of obtaining a representative loading stratigraphy from such sediments. It is perhaps possible that the scavenging of trace metals by iron and manganese oxyhydroxides in the oxic layer could serve a beneficial function, by reducing the bio-availability of toxic metals that do accumulate in the lake.

The 'deep' lakes studied in Keewatin represent highly oligotrophic limnologic systems, possibly in part because of the strong sequestering of a prime nutrient (phosphorous) within the underlying sediments. As a result, such lakes may be extremely sensitive to disruption of the chemical stratification in the upper sediment layers, which might be triggered by such factors as hypolimnetic anoxia induced naturally under prolonged ice-cover or through accelerated oxygen depletion due to hydrocarbon or sewage spills. (Some studies have been conducted in Keewatin to assess the effect of a natural gas leak into an ice-covered lake (Welch et al. 1980).) Alteration of the geochemical milieu in the bottom sediments and potential mobilization of stored substances (perhaps including nutrients and trace metals) could result also from changes in the sedimentary regime, as might occur from siltation associated with local terrain disturbance through fire or through human activity. Increased water turbidity alone could markedly affect phytoplankton production, which forms the basis of the aquatic food chain.

The 'shallow' lakes and ponds in Keewatin represent more productive aquatic systems than the deeper lakes, although they are probably somewhat less productive than their counterparts at lower latitudes. A notable exception to the typical clear-water lakes, however, are the so-called 'turbid lakes', which are shallow, flat-bottomed lakes that occur scattered sparsely, mainly below the maximum marine limit (Aylesworth et al. 1981). Such lakes contain high concentrations of suspended sediment that is apparently derived from underlying fine-grained deposits, stirred up during spring break-up and maintained in the water column by wind-generated turbulence until freezing in the fall. Examination of a turbid lake near Kaminak Lake revealed a profusion of biota, including sponges and phyllopods (freshwater shrimps) not observed in other lakes, evidently favoured by high water temperatures and an absence of predatory fish. Turbid conditions are known to have recurred in some lakes over several successive summers, but it is not known how long this may continue, nor why turbid lakes and clear lakes commonly co-exist side-by-side in seemingly identical situations. Although turbid lakes contain only a minute fraction of present surface waters, knowledge of the factors controlling their genesis could be important to our understanding of the history and future of clear-water lakes and ponds, especially in the vast area below marine limit.

Some indication of the rate of contemporary environmental change in District of Keewatin may be obtained from re-examination of sites studied by Geological Survey of Canada personnel (or others) in previous field operations. Divers in the 1970's noted significant alteration of materials discarded in earlier field operations. Resampling of lake waters or sediments initially sampled ten to fifteen years ago might yield information about possible recent changes in pH, heavy metal content, or other parameters. Especially definitive data about the modern sedimentation rate and sediment geochemistry in an arctic lake should be obtained upon eventual retrieval of sediment traps and pans and metal rods of various compositions emplaced by the senior author at several sites in 'Whatever' Lake in 1977.

ADDITIONAL COMMENTS

The primary objective of this article is to direct attention to a substantial body of information collected by the Geological Survey of Canada and judged to have potential significance to current environmental concerns in the North. Based on the knowledge and experience gained from these studies, several observations and recommendations are offered for consideration.

1) Strategies for water quality monitoring in the District of Keewatin should focus on lakes, and particularly on the larger lakes that harbour important fish populations. The little monitoring that has been done on river waters (Environment Canada 1986) has limited applicability to the much more
extensive aquatic resource represented by lakes and ponds.

2) On-going research should be considered an essential part of an effective monitoring strategy to allow continual reassessment of the monitoring programs and foster improved understanding of the natural systems under scrutiny. Specific research topics suggested by the investigations outlined above include studies of the acid neutralizing capacity of lake sediments, interchange of nutrients and metals between lake sediments and waters, interaction between groundwaters and lakewaters, sensitivity of sublacustrine permafrost to climatic change, biotic responses to natural heavy metal contamination, effects of tundra fires on limnic systems, genesis and history of turbid lakes, rates of degradation of anthropogenic or natural bottom debris, rates of sedimentation, and so on.

3) Some of the most glaring omissions in our understanding of arctic environments in general, and arctic lakes in particular, stem from the paucity of information about conditions during the winter. The initial stages (at least) of any effective monitoring strategy in the North will require extensive collection of very basic information during the winter months.

4) Finally, it is worth noting that other sources of data do exist, in the form of mining assessment reports, environmental impact statements (in particular those prepared for the Polargas pipeline proposal), and other documents that may contain information having pertinence to water quality concerns. The potential value of background information that may be derived from such 'proxy' sources (including those discussed here) should not be ignored in the urgency of establishing new monitoring programs.

ACKNOWLEDGEMENTS

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