Surficial geochemistry, south-central Canadian Shield: implications for environmental assessment

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ABSTRACT


An ongoing problem in evaluating the effects of acid rain is distinguishing natural (spatial) variations of the geochemical environment from anthropogenic (temporal) variations. In other words, it is important to determine whether a lake is naturally acid because of its geological setting or whether it has been acidified as a result of dry and wet acid deposition.

To provide a model that might aid in answering these questions, the Geological Survey of Canada has carried out a series of sampling programs on the south-central part of the geologically complex Canadian Shield. With these programs we have tried to link the easily observable lithological variations of bedrock with the chemical composition of overlying glacial deposits with the geochemical compositions of lake sediments and lake waters. Presumably, once these linkages are understood, variations in life systems that inhabit terrestrial and aquatic environments in the areas sampled with be easier to evaluate. The ultimate goal is to provide a base against which observed variations in life systems can be judged as natural or anthropogenic. In addition, sound geological data can be used to refine estimates of SO$_2$ and NO$_x$ target loadings and to determine areas where acid deposition may mobilize potentially noxious trace metals into the hydrologic cycle.

The importance of establishing geological and geochemical linkages is illustrated by the fact that significant parts of the Canadian Shield, while formed of granitoid rock, are overlain by calcareous unconsolidated sediments that have been glacially transported long distances from limestone sources. For instance, in areas north of Lake Superior and Eastern Ontario, high concentrations of carbonate minerals in glacial sediments overlying carbonate-poor bedrock result from glacial transport of carbonate minerals tens to hundreds of kilometres from limestones on their up-ice sides. In these same areas, high concentrations of As, Hg and other trace elements in sediment and water can be related to glacial dispersal from bedrock known to host mineralized occurrences or high background concentrations of these elements.

Awareness of bedrock composition and of glacial distortion of the chemical signature of bedrock is essential for insuring that a complete and credible database is provided to the legislators and regulatory agencies charged with establishing realistic target loadings for acid deposition.
INTRODUCTION

Exploration geochemists and geologists who routinely gather and compile information relating to the natural chemical status of the surficial environment usually do so to provide targets for mineral exploration or to evaluate mineral potential on a regional basis. Often overlooked by geochemists and environmental scientists alike is the fact that these mineral-exploration-related data can provide important baseline information defining the natural status of the environment. It is only with an appreciation of natural compositional variations of the geological substrate on which life systems are superimposed that scientists from other disciplines can evaluate the extent to which man has affected the chemistry of these systems. Thus, we suggest that exploration geochemical data gathered in the past and in the future can have significant value in assessing environmental impact of such anthropogenic phenomena as acid rain. In this paper, we attempt to show how certain geochemical data, collected routinely for mineral exploration purposes, can be used to distinguish natural from anthropogenic variations of the surficial environment.

The primary problem in documenting effects of acid rain is separating natural, spatial variations, sometimes referred to in environmental literature as the "status" of a landscape, from anthropogenic, i.e., temporal variations. For example, many reports on acid rain refer to lakes with low pH as "acidified", implying recent acidification. The adjective "acid" is preferable to "acidified" because it refers solely to the chemical status of the lake, with no implication of whether the status was achieved naturally because of geological setting or anthropogenically because of recent atmospheric modification. Lakes in geologically complex terrains, such as the Canadian Shield, have a wide natural range of acidities that are clearly related to their geological setting (Coker and Shilts, 1979; Hornbrook et al., 1986). The challenge for geochemists and geologists, then, is to devise ways to distinguish among natural and anthropogenic factors that influence acidity of the landscape in order to provide environmental scientists with meaningful and credible techniques or strategies for discerning the true effects of acid rain.

In considering the composition of lakes and adjacent surficial sediment, the geochemist can measure a number of parameters that bear on the effects of various types of atmospheric pollution. Among the most important of these parameters is the measurement of regional variations of buffering components, the carbonate minerals and clay-sized particles that adsorb or react with excess protons associated with atmospheric acids. In this study, the variation in carbonate concentrations and buffering effects of carbonate minerals in drift clearly are related to variations in pH and alkalinities of lake waters.

A second important parameter, and one provided by exploration geochemical surveys, is the pattern of natural variation of metal concentrations in ter-
restrial and aquatic systems. Although terrain "sensitivity" to acid rain generally is evaluated in terms of the ability of surficial sediments to buffer pH, trace-element variations also are important indicators of the types of potential damage that may be generated by excess atmospheric acids. Although most metals reside in mineral phases that are stable under present environmental conditions, they can be displaced into the hydrogeologic system by protons from the excess atmospheric acids created by anthropogenic activity, and mobile forms may be elevated to potentially noxious levels in the absence of buffering components. Thus, it is useful to know the natural distribution and concentrations of metals in surficial sediments in order to predict where the worst effects of cation mobilization by acid rain may occur.

Finally, knowledge of patterns of natural distribution of metals in lakes and soils aids evaluation of the extent to which these same metal species, released along with sulphur and nitrogen compounds into the atmosphere, are deposited on the landscape. Such patterns are becoming increasingly important be-

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Fig. 1. Bedrock geology, Frontenac Arch area, southeastern Ontario, modified after Baer et al. (1977). Locations of Frontenac Arch and Lake Superior study areas are shown.
cause of increasing reference in the environmental literature to elevated concentrations near the top of postglacial sediment cores of one metal or another, Cu, Zn and Pb in particular, as evidence of anthropogenic deposition (Carignan and Tessier, 1985; Norton, 1986; Lazerte, 1986). Deposition of anthropogenic metals from atmospheric fallout undoubtedly is widespread, but confusing natural areal and in situ variations with anthropogenic variations cannot help but muddy the picture and obscure the priorities for emissions modifications.

To provide data that might aid in evaluating the problems cited above, the Geological Survey of Canada carried out a pilot project in which surficial sediment was sampled over geologically complex terrain of the Canadian Shield in the Frontenac Arch area of southeastern Ontario (Fig. 1; Kettles and Shilts, 1983; Kettles, 1988). In the same area, geochemical data were collected for lake sediment and lake water (Geological Survey of Canada, 1977a,b; Hornbrook et al., 1984a,b). Lake water and sediment data from the north shore of Lake Superior (Fig. 1), originally collected for mineral resource evaluation, also were reevaluated from an environmental perspective (Geological Survey of Canada, 1978a,b, 1979a,).

SAMPLE COLLECTION, PREPARATION AND ANALYTICAL METHODS

In the study area north of Lake Superior, 4293 samples (1 per 13 km²) of centre-lake sediment and an equal number of surface lake water samples were collected (Coker and Shilts, 1979; Coker et al., 1979; Fig. 1). Sediment samples were obtained using a Geological Survey sampler (Coker et al., 1979) deployed from a winch-equipped helicopter. Surficial (top 5–10 cm) sediment was automatically excluded through sampler design. The majority of the samples were brown, green-brown (olive), or black, organic-rich gelatinous sediments. Surface lake water was collected in 250-ml polyethylene bottles.

The <180 \mu m fraction of the lake sediment samples was analyzed for Zn, Cu, Pb, Ni, Co, Ag, Mo, Mn and Fe using atomic absorption spectroscopy techniques. Part of the sample set was analyzed for As using colorimetric methods and the remainder using the hydride evolution method (Aslin, 1976). Mercury contents of the lake sediments were determined by the Hatch and Ott procedure, with some modifications (Jonasson et al., 1973). Uranium was determined by neutron activation methods (Boulanger et al., 1975), and loss-on-ignition (L.O.I.) by ashing the sediment during a three-hour time-temperature–controlled rise to 500°C.

Untreated water samples were analyzed for F and pH using a specific-ion electrode and glass-calomel combination electrode, respectively. Uranium was determined by fission track analysis (McCorkell, 1983).

In south-central Ontario, lake water and sediment samples were collected
from approximately 2200 lakes (1 per 13 km²) (Hornbrook et al., 1984a,b; Fig. 1) and analyzed using techniques similar to those described above. Over the same area, glacial sediments, primarily till, were sampled at irregular intervals from below the postglacial solum at easily accessible man-made excavations and natural exposures along streams and rivers, resulting in a sample density of about 1 per 23 km² (Kettles and Shilts, 1983). In the Ottawa River Valley and the St. Lawrence River Valley, marine silty clay and proglacial lacustrine silty clay, which form an almost continuous surficial cover in lower areas, were sampled. The clay (<2 µm) and silt-clay (<63 µm) fractions were separated from each of the samples by centrifugation and by sieving, respectively. Trace- and minor-element concentrations were determined for the clay fraction by atomic absorption techniques using a hot HCl-HNO₃ leach (Cu, Pb, Zn, Co, Ni, Ag, Cr, Fe, Mn and Cd), colorimetric methods (As) and fluorimetric methods (U). Carbonate determinations were made on the <63 µm fraction using a Leco Carbon Analyzer. The differences between carbon present in leached and unleached splits of the same sample were converted to weight per cent CaCO₃ using a formula from Foscolos and Barefoot (1970). Paleozoic limestone and dolomite erratics were separated from the granule-pebble fraction (2–6 mm) and their weight per cent of the granule-pebble fraction calculated. Grain size composition of the <2 mm fraction was determined using standard sieve and pipette procedures.

Results of analyses for both study regions along with sample locations and descriptions were stored on computer files. Geochemical data were plotted and contoured using a computer package (APPMAP) developed by D.J. Ellwood of the Geological Survey of Canada.

GENERAL GEOLOGY

The distribution of various bedrock lithologies influences the regional elemental distribution within the secondary environment; secondary geochemical patterns may be a function of the mineralogy of specific lithologic units and associated metal deposit types. Over most of Canada, however, it is not possible to predict the response of the terrain to acid loading solely on the basis of bedrock composition (Shilts, 1981). The cover of glacial drift may have a chemical composition that is considerably different from that of underlying bedrock. Where present, glacial deposits may be more chemically reactive than surficial sediments typically found beyond the glacial limit. Because they are formed by processes of mechanical breakdown (crushing and abrasion), glacial deposits are composed largely of unweathered, easily altered mineral fragments rather than the stable secondary minerals typically produced over long periods of chemical weathering in unglaciated terrain. Also, glacial lakes and postglacial seas flooded parts of the country leaving fine-grained, relatively impermeable sediments over large areas (Shilts, 1981).
For these reasons, the regional bedrock geology, metallogeny, bedrock geochemistry and glacial geology are reviewed for both study regions.

Geologic setting of the Frontenac Arch area

Two main types of bedrock terrain are distinguished in the Frontenac Arch area (Baer et al., 1977; Fig. 1). To the east and south, flat-lying, unmetamorphosed Ordovician limestones, dolomites and shales underlie the Central and West St. Lawrence Lowlands Physiographic Region (Bostock, 1970). The remainder of the study area is underlain by Archean to Helikian rocks of the Grenville Structural Province of the Canadian Shield. The western part of the Grenville terrain is underlain by rocks of the Ontario Gneiss Belt and the eastern part by rocks of the Central Metasedimentary Belt (Baer et al., 1977). Sangster (1982) describes the latter as comprising a thick basal series of metavolcanic rocks overlain by intercalated marbles and arkosic metasedimentary rocks. These, in turn, are cut by rocks of at least two intrusive suites, overlain by younger metasedimentary rocks. The Frontenac Arch is a structural feature forming a narrow neck of Precambrian outcrop that connects the Canadian Shield to the main body of the Adirondack Mountains south of the St. Lawrence River.

According to Sangster (1982), the most important mineral deposit types in the Frontenac Arch area are:

1. stratiform deposits including oxide and sulphide facies iron formation, and zinc deposits in carbonate rocks;
2. magmatic deposits of Ni-Cu and Fe;
3. metasomatic deposits, predominantly Fe skarns;
4. quartz-vein deposits of Au and base metals; and
5. post-Ordovician veins containing calcite, fluorite, harite, galena and/or celestite.

The predominant ice flow direction during the last glaciation was towards the south-southwest. During deglaciation, one lobe of ice flowed southwestward, its front retreating eastward from Lake Ontario down the St. Lawrence Valley, and another flowed south-southeastward, retreating northwestward up to the Ottawa Valley (Richard, 1975; Gadd, 1980). The late-glacial flow patterns do not appear to have influenced drift composition, most dispersal being in the south-southwestward direction.

Stratigraphically, only one unit of till which forms a thin cover (0–5 m thick) over both Precambrian and Paleozoic bedrock of the region, has been identified in the area sampled. Till can be thicker in depressions, along valley walls, on the up-ice side of bedrock ridges, and on the down-ice side of bedrock knobs. Along the Ottawa and St. Lawrence valleys and in low-lying areas near Georgian Bay, glaciomarine and glaciolacustrine sediments form a fairly continuous surface cover. The Ottawa and lower St. Lawrence Valleys were
inundated by Champlain Sea during late-glacial times, whereas the low areas in the southern and western parts of the Frontenac Arch were flooded by glacial Lakes Iroquois and Algonquin, respectively (Fig. 2).

Geologic setting of the north shore of Lake Superior

Archean bedrock of the Superior Province is composed of large east-trending metavolcanic and metasedimentary supracrustal remnants intruded and partly surrounded by composite granodioritic batholiths and tonalitic gneiss domains (Goodwin, 1972; Fig. 3). The Southern Province consists largely of Proterozoic bedrock which was unconformably deposited on deformed Archean basement, and later slightly deformed and metamorphosed (Card et al., 1972). The Proterozoic supracrustal rocks consist of: Aphebian sedimentary rocks of the Animikie Group, Gunflint and Rove Formations; Helikian sedimentary rocks of the Sibley Group; basalt with minor acid volcanic and
Fig. 3. Bedrock geology and mineral occurrences, north shore, Lake Superior, Ontario (modified from Coker and Shilts (1979) based on work by Ayres et al. (1971a,b) and Springer (1977a,b,c; 1978a,b,c,d,e)).
sedimentary rocks of the Osler Group, intrusions, including Logan diabase sills, alkaline complexes, including the Port Coldwell bodies, and carbonatite complexes; and a Hadrynian clastic redbed sequence, the Jacobsville Formation, underlying much of Lake Superior (Card et al., 1972). Northeast of the study area, Paleozoic strata of the Hudson Bay Lowlands are dominated by limestones and dolomites. In the same area poorly consolidated, kaolin-cemented sandstone interbedded with lignite and clay comprise a late Mesozoic sequence overlying the Paleozoic strata.

The four main classes of mineral deposits are:

(1) stratiform deposits, including Archean volcanogenic massive sulphide, iron formation, and gold;

Fig. 4. Generalized glacial dispersal directions and selected bedrock and glacial features for the Lake Superior study area and adjacent regions. Total carbonate contents (weight % CaCO₃ equivalent) determined on 44–63 µm fraction of till collected at > 3 m depth from boreholes drilled to explore the route for the Polar Gas pipeline.
Fig. 5. The distribution of carbonate (% CaCO₃ equivalent) in silt plus clay-sized (<63 μm) fraction of glacial drift, Frontenac Arch area, southeastern Ontario.
(2) intrusion-hosted deposits, including Ni-Cu-Pt and alkalic and carbonatitic deposits;
(3) veins—Ag-Pb-Zn-Cu, Pb-Zn-Ag, pitchblende, Pb-Zn-Ba-amethyst, uraniferous apatite, Cu and Au; and
(4) breccia pipes.
Approximately 300 bedrock samples collected over the Lake Superior area were analyzed for trace and minor elements (Coker and Shilts, 1979). Results indicate that the Coldwell complex has very high levels of F, high levels of Mo and Zn, moderately high levels of U, Cu, Mn and some Pb, Co and Fe enrichment. Very high concentrations of Cu, Ni and Co, and high concentrations of Fe are associated with diabase. The Sibley Group rocks have high Zn, Ag, As and Hg contents. The Animikie Group (Rove and Gunflint formations) have very high concentrations of Hg and high concentrations of Zn, Ag, As and Mn. Archean pegmatites are highly enriched in U and also have high levels of Pb and Mo.
The Lake Superior study area lies directly down-ice from the major Paleozoic carbonate basin of Hudson Bay (Fig. 4). Although the predominant ice flow direction was southerly and southwesterly (Prest, 1970) during retreat of the last ice sheet, lobes were formed either by ice flow channeled along major structural depressions or by surging of unstable ice fronts into glacial lakes. These last ice movements were in some cases at considerable angles to general flow patterns during the maximum development of the Labradorian sector (Prest, 1984) of the ice sheet, but, like the lobes in the Frontenac Arch area, they probably caused only local distortions of the northerly provenance of the drift. Also, during recession of the ice sheet, proglacial Lake Algonquin formed in Lake Superior and adjoining basins (Fig. 4). Zoltai (1965) and Boissonneau (1966) reported areas of varved clay in low-lying areas along the north shore of Lake Superior and in the northeastern part of the study area, respectively.

GLACIAL AND LAKE SEDIMENT AND LAKE WATER COMPOSITION

Distribution patterns of the buffering components

Drift in the eastern and southern parts of the Frontenac Arch contains substantial amounts of carbonate minerals (Fig. 5) (Shilts, 1984; Kettles and Shilts, 1989). In the eastern part of the Frontenac Arch area, marble contributes some carbonate to local drift, especially in the carbonate-rich area located west and south of Denbigh. Most carbonate, however, is derived from Paleozoic carbonates, a conclusion supported by evidence of carbonate enrichment in samples with high concentrations of Paleozoic fragments (Shilts, 1984). Even in drift directly overlying marble in the western part of the study area, carbonate concentrations are significantly less than those of drift with
Fig. 6. The distribution of clay-sized detritus (<4 μm) in the <2 mm fraction of till and glaciomarine/glaciolacustrine silty clays, Frontenac Arch area, southeastern Ontario.
high concentrations of Paleozoic rock types on all bedrock types in the eastern region.

In the Lake Superior area, highest concentrations of carbonate (up to 40%) are found in tills in the Nipigon region, derived from and overlying the red dolomitic shales of the Sibley Formation, (Zoltai, 1965; Coker and Shiits, 1979).

In all other parts of the Lake Superior study area, carbonate minerals in the drift are derived from Paleozoic carbonates of the Hudson Bay Lowlands which is located 50 kilometres or more to the north of the northeast corner of the area sampled (Fig. 4) (Zoltai, 1965; Boissonneau, 1966). Tills in the Wawa–White River–Hornpayne areas contain 15–25% carbonate (Boissonneau, 1966), as do tills north of the study area (Fig. 4; Coker and Shilts, 1979). In contrast, in the western part of the Lake Superior study region north and west of Thunder Bay, calcareous till is not found over large continuous areas (Zoltai, 1965). Rather it occurs in small isolated areas (up to 10 km²) which frequently take the form of drumlins.

Tills containing substantial quantities (> 20%) of Paleozoic fragments in the eastern and southern parts of the Frontenac Arch area contain large quantities of clay-sized detritus (> 5%) (Fig. 6) compared with other samples. The influence of Paleozoic lithologies on texture, as well as carbonate composition in both areas, can be attributed to physical characteristics of Paleozoic strata. The highly jointed, horizontally bedded, fine-grained nature of outcrops of sedimentary bedrock of the Hudson Bay and St. Lawrence Lowlands caused it to be more susceptible to glacial erosion than Precambrian lithologies, which are massive and coarsely crystalline. Resulting high concentrations of Paleozoic debris within the ice are thought to have favoured comminution by clast-on-clast impacts during transport. The resulting abrasion is thought to have produced a large volume of fine-grained, calcareous rock flour that was transported across the Frontenac Arch and incorporated into till.

As would be expected, lakes on the Frontenac Arch (Fig. 7) and north of Lake Superior (Fig. 8) are more alkaline where there are large continuous areas covered with carbonate-rich drift (Coker and Shilts, 1979; Hornbrook et al., 1986). Lake water pH appears to be an even more sensitive and reliable indicator of the presence of small amounts of carbonate in drift than is the chemistry of drift itself. For example, even where carbonate is barely detectable in surficial sediments over the marble belts in the western part of the Frontenac Arch, lake waters are more alkaline than nearby lakes on non-carbonate lithologies.

Lakes are also neutral to basic in areas underlain by carbonate members of the Sibley Group, northeast of Thunder Bay and east and west of Nipigon–Red Rock (Fig. 8). High pH is also characteristic of water in lakes overlying
Fig. 7. Levels of pH in lake waters, Frontenac Arch area, southeastern Ontario, modified after Hornbrook et al. (1986).
Fig. 8. Levels of pH in lake waters, north shore, Lake Superior, Ontario.
Fig. 9. Arsenic in the clay (<2 μm) fraction of glacial sediments. Frontenac Arch area, southeastern Ontario.
carbonate facies iron formations northeast of Wawa on the east shore of Lake Superior (Coker and Shilts, 1979).

Felsic igneous and gneissic rocks (Unit 5 on Fig. 3) underlie the eastern shore of Lake Superior, south of Wawa, and crop out north of Thunder Bay. While both areas lack a continuous cover of carbonate-rich drift, lake waters east of Lake Superior are highly acid, whereas those north of Thunder Bay are generally neutral to slightly acid (Coker and Shilts, 1979). Since the eastern shore is at times subjected to surface winds that pass through the east-central United States (Bryson, 1966), the dominant source of sulphur dioxide and nitrogen oxide emissions in North America (Voldner and Shah, 1979), it is possible that the pH of the east-shore lakes has been depressed as a result of acid precipitation. Similarly, acid lake water in the otherwise alkaline area at Nipigon-Red Rock, at Schreiber-Terrace Bay, and at Marathon may be related to local emissions from pulp- and paper-manufacturing operations.

Distribution patterns of trace elements

The dispersal patterns of many trace elements reflect the composition of underlying bedrock. The large areas of arsenic enrichment in drift in the Frontenac Arch (Fig. 9) broadly outline prominent belts of metavolcanic and metasedimentary rock of the Central Metasedimentary Belt (Shilts, 1984; Kettles and Shilts, 1989) as do areas with high As content in lake sediments (Fig. 10; Hornbrook et al., 1986). Arsenic-bearing minerals are known to occur in association with quartz vein-hosted sulphide deposits within metavolcanic and clastic sedimentary and carbonate rocks (Sangster, 1982). Individual deposits are small, however, and detailed studies of drift dispersal in the Frontenac Arch area (Sinclair, 1979; DiLabio et al., 1982) show that detectable dispersal from sulphide occurrences in the marble is on the order of 1 km. Elevated As concentrations in drift over such a large area may indicate that there are high background concentrations of As in other mineral phases in the metasedimentary and metavolcanic host rocks themselves.

High concentrations of As in lake sediments (Fig. 11) of the Lake Superior area also appear to be related to bedrock lithologies or to sulphide mineralization (Coker and Shilts, 1979). Areas of As enrichment in lake sediments (Fig. 11) can be related to: (1) arsenical iron formation at Wawa, although in this case some enrichment may also be related to the plume from the local iron smelter; and (2) the Rove and Gunflint formations of the Animikie Group, west and southwest of Thunder Bay. Arsenic is also enriched in lakes over the Kama Hill Formation of the Sibley Group, west of Nipigon-Red Rock, in lakes over various sulphide and gold occurrences, and in lakes on arsenic-bearing Archean pegmatite and metasedimentary rock terrane throughout the survey region (Fig. 11).

Areas of Pb enrichment in drift over the Frontenac Arch (Fig. 12) gener-
Fig. 10. Arsenic in the < 180 μm fraction of lake sediments, Frontenac Arch area, southeastern Ontario, modified after Hornbrook et al. (1986).
Fig. 11. Arsenic in the < 180 μm fraction of lake sediments, north shore, Lake Superior, Ontario. (Locations of mineral occurrences are shown on Fig. 3).
Fig. 12. Lead in the clay (<2 μm) fraction of glacial sediments. Frontenac Arch area, southeastern Ontario.
ally are underlain by carbonate metasedimentary or metavolcanic rocks of
the Central Metasedimentary Belt. Areas with high Pb concentrations in drift
generally correspond to those with high levels of As (Fig. 9), Hg, Co, Mn and
Fe (not shown), all of which are elements associated with sulphide minerali-
zation. The distribution of Pb in lake sediments over the same area (not
shown) is less easily related to the geology as the areas of enrichment are
numerous, small and widely dispersed.

In the Lake Superior area, Pb levels are high around the shore of Lake Su-
perior and around Hornepayne (Fig. 13). There are many possible explana-
tions for these high Pb levels. Some Pb enrichment in these regions may be
due to human activities. For instance, lead shot has been observed in lake
bottom sediments collected around Hornepayne, a popular hunting ground.
It is possible that some high Pb levels on the eastern shore could be caused by
airborne dustfall or by mobilization of Pb in lake sediment as a result of aci-
dification of water and soils. This region is crossed also by winds which have
passed through the industrialized east-central region of the United States.

There are, however, several possible explanations for natural Pb enrich-
ment around Lake Superior. Many of the areas of greatest enrichment corre-
spond to regions where Pb mineralization in Archean pegmatites is known to
occur. Lead concentrations are also persistently high in those areas outlined
in Figure 4 which were covered by Glacial Lake Algonquin, and the predom-
inant surface sediment is lacustrine sand, silt and clay. Trace-element levels
in glaciolacustrine sediments in most cases reflect the average composition of
the clay fraction of rock flour suspended in meltwater flowing into the lake
basin. The rock flour, in turn, was derived from many lithologically different
source areas on the glacier's bed before being homogenized in the lake and
widely dispersed over the flooded areas. It is possible then, that in an area
such as the one north of Lake Superior, where there are numerous known
occurrences of Pb in bedrock, background concentrations of Pb may be ele-
vated in glaciolacustrine sediment as a result of homogenization during sedi-
mentation. These high background levels in turn may be reflected in modern
lake sediment, which derives its geochemical characteristics from the uncon-
solidated surface cover. Similar patterns of Cr enrichment in glaciolacustrine
and glaciomarine sediments have been observed in Keewatin (Shilts, 1980)
and in southwestern Quebec (Kettles and Shilts, 1989).

In the Frontenac Arch area, the distribution of U in glacial sediments (Fig.
14) corresponds to its distribution in lake sediments (not shown here) but
bears only a vague resemblance to its distribution in lake waters (Fig. 15;
Hornbrook et al., 1986). In contrast, patterns of U enrichment in lake water
closely mimic, regionally, patterns of high pH (Fig. 7) and alkalinites (not
shown) in lake waters and high carbonate concentrations in drift (Fig. 5).
This suggests that, in this area, U is more soluble/less adsorbed in an alkaline
lacustrine environment. On the north shore of Lake Superior, areas with high
Fig. 13. Lead in the < 180 μm fraction of lake sediments, north shore, Lake Superior, Ontario.
Fig. 14. Uranium in the clay (<2 μm) fraction of glacial sediments, Frontenac Arch area, southeastern Ontario.
Fig. 15. Uranium in lake waters, Frontenac Arch area, southeastern Ontario, modified after Hornbrook et al. (1986).
Fig. 16. Uranium in lake waters, north shore, Lake Superior, Ontario.
pH (Fig. 8), high alkalinity (not shown) and elevated concentrations of U in lake waters (Fig. 16), tend to correspond, but the distribution pattern of U in lake sediment and water appears to be more strongly influenced by bedrock composition than in the Frontenac Arch area. Areas of uranium enrichment in the eastern and western parts of the Lake Superior area are coincident with the White River-Manitouwadge pegmatite fields and with sedimentary rocks of the Sibley Group, respectively.

DISCUSSION AND CONCLUSIONS

The examples of variation of pH and U in lake waters, As and Pb in modern lake sediments, and carbonate, clay, As, Pb and U in glacial sediments over the Frontenac Arch and Lake Superior study areas, illustrate the strong and predictable influence of geology on patterns of chemical variation. These data show the types of geochemical information that can be brought to bear on the evaluation of the nature and extent of anthropogenic modifications of natural chemical systems. For example, knowing the areas where As and Pb are naturally enhanced in lakes, glacial drift and/or bedrock, offers some hope for identifying areas where these potentially toxic elements may accumulate to dangerous concentrations in an “acidified” landscape. It also may lead to a realistic evaluation of the extent to which these elements are enriched in the surficial environment due to fallout as airborne pollutants. If As, Pb and other trace elements in lake sediments, glacial drift and associated soils are bound in relatively stable forms under present natural environmental conditions, significant decreases in soil and/or water pH may upset the natural equilibrium. If enclosing sediments are saturated with protons these and other metals could be released into surface and ground waters in potentially noxious forms, for eventual uptake by vegetation and terrestrial or aquatic organisms.

In most cases, the geochemical variation of glacial drift, lake sediment and lake water is related to chemical characteristics of the bedrock in or adjacent to the lake’s drainage basin. Over much of Canada, however, the bedrock geochemical signature can be distorted, often significantly, by glacial transport of material which imparts its own characteristic buffering effects and trace element chemical variations (Shilts et al., 1981). In the Frontenac Arch and Lake Superior areas, glacial dispersal of carbonate erratics from the Ottawa-St. Lawrence and Hudson Bay lowlands has had a significant regional effect on glacial drift, lake sediment and lake water composition.

From these discussions two major conclusions may be drawn:

1. Variation in the pH of lake waters can be predicted to a large extent on the basis of a knowledge of glacial and bedrock geology and can be significant over a geologically complex region. Acid conditions in lakes may be natural, reflecting their postglacial “status”, and are not necessarily the result of anthropogenic “acidification”.
(2) Knowledge of natural patterns of elevated metal concentrations in glacial drift and lake sediments can be used to "pinpoint" locations where pH reduction as a result of anthropogenic acid precipitation might cause potentially noxious components to be released into hydrologic systems, and into the surficial environment in general. It can be used also to evaluate realistically the importance of the flux of atmospheric contaminants that may accompany acid emissions.

REFERENCES


